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Progress in Kinetic Edge Simulations

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edge
simulation
laboratory

Plasma Edge Theory Meeting

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OUTLINE

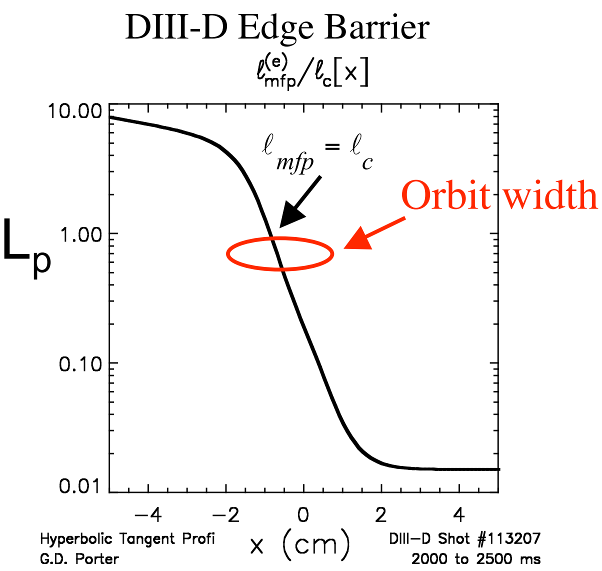
Edge Simulation Laboratory

- The challenge of the edge for kinetic simulation
- Remarks on formalism
- The major approaches: PIC and continuum
- Survey of kinetic edge simulation efforts
  - Scope: consider only 2+ spatial dimension, drift or gyrokinetic
    - Plus one exception: a full-ion-dynamics 2D code that does divertor geometry
- Summary of recent results from ESL codes (TEMPEST, EGK)
- Conclusions

Why we need kinetic edge simulation

- Conventional wisdom: the edge is dense and cold; fluids are fine.   But:

- Still need to be kinetic because:
  - Ion drift orbit width Δ ~ pedestal width L_p
  - Mean free path ~ connection length



The edge presents challenges not found in core kinetic simulation

edge simulation laboratory

- Overlap of scales: a priori unknown $f_0(v)$ (versus δf applicable in core)
- Large-amplitude fluctuations (another problem for δf)
  - Blobs
  - ELMs
  - L-mode turbulence
- Large n and T contrast across edge pedestal and into divertor regions
  - Presents challenge for particle count (PIC, noise) or v-space grid requirements (continuum, accuracy)
  - Presence of cold, dense regions $\Rightarrow$ need accurate collision operator
- 2D plasma equilibrium with large equilibrium $\Phi(x)$
  - Can't exploit zero-order constancy of speed as in core
- Overlap of scales $\Rightarrow$ extensions to gyrokinetic theory
  - But $\omega << \Omega_c \Rightarrow$ gyrokinetics still useful
- PLUS most the complications of edge fluid codes (geometry, atomic physics, neutrals, impurities,…)

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Gyrokinetic formalism requires extension

- Starting point (and ending point for many simulation projects): Vlasov-Fokker-Planck equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f + (\mathbf{E} + \mathbf{v} \times \mathbf{B}/c)\nabla_v f = C(f) \qquad (1)$$

- Gyrokinetics: a reduction of above equation that eliminates fast gyromotion.
- Traditional derivations of gyrokinetics made assumptions that break down in edge, e.g.
  - $e\phi/T << 1$
  - $\delta f/f << 1$ (related: orbit size/L << 1)
- Theory advances have led to increased applicability usually with added complexity.
  - Notable exception: Dimits et al (1992) recognize that earlier work (Hahm '88) is more applicable than claimed, requiring $v_{ExB} << v_{th}$ rather than $e\phi/T << 1$. This means can simulate long scale-length phenomena with $e\phi/T \sim 1$

New formulations applicable to the edge but complicated

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- Qin, last PET meeting, and APS-DPP 2006, find coordinates with symmetries that eliminate gyrophase dependence.
  - Assumtions: $f = f_0+f_1$ and similarly for ϕ, A; “0” quantites abitrary amplitude long wavelength; “1” quantities small amplitude abitrary wavelength.
  - Gives a complicated GK equation (which involves solving for a 6D generating function!).
  - Simplifications to generating function allow reduced equations that preserve conservation properties (phase space volume, energy-momentum).
  - Example: electrostatics in time-independent inhomogeneous background E, B, low frequency
  - Ref. PoP May 2007.

Qin's simplified equations (time-independent B_0, E_0)

$$\frac{\partial F}{\partial t} + \frac{d\mathbf{X}}{dt} \cdot \nabla F + \frac{du}{dt}\frac{\partial F}{\partial u} = 0 \qquad (2)$$

with u the paralllel velocity, and

$$\frac{d\mathbf{X}}{dt} = \frac{\mathbf{B}^\dagger}{B_\parallel^\dagger}\left(u + \frac{\mu}{2}\mathbf{b}\cdot\nabla\times\mathbf{b}\right) - \frac{\mathbf{b}\times\mathbf{E}^\dagger}{B_\parallel^\dagger} \qquad (3)$$

$$du/dt = \mathbf{B}^\dagger\cdot\mathbf{E}^\dagger/B_\parallel^\dagger, \mathbf{B}^\dagger = \nabla\times\mathbf{A}^\dagger, \mathbf{A}^\dagger = A_0 + u\mathbf{b} + \mathbf{D}, B_\parallel^\dagger = \mathbf{B}^\dagger\cdot\mathbf{b},$$

$$\mathbf{E}^\dagger = -\nabla[\phi_0 + \mu B_0 + (D^2/2) + \langle\psi_1 + \psi_2\rangle, \quad \mathrm{D} = \mathrm{v}_{\mathrm{E_0}\times\mathrm{B}}$$

$$\psi_1 = \langle\phi_1(\mathbf{X}+\rho)\rangle, \psi_2 = -\left\langle\nabla\tilde{\phi}_1\cdot\nabla\phi_1^{(1)}\right\rangle \times (\mathbf{b}/2B_\parallel^\dagger\overline{B}_0) - (1/2B_0)\left\langle\partial\tilde{\phi}_1^2/\partial\mu\right\rangle.$$

$$\phi_1^{(1)} = \int \phi(\mathbf{x}+\rho)\,d\theta$$

- Field equation: $\nabla^2(\phi_1 + \phi_0) = -\sum 4\pi q n$, where

$$n(x) = \int \Big[\underbrace{F}_{\text{g.c.+FLR}} + \underbrace{\frac{\partial F}{\partial\mu}\frac{\tilde{\phi}_1}{B_0}}_{\text{Polariz.}} + \underbrace{\nabla F \times \frac{\nabla\tilde{\phi}_1^{(1)}}{B_\parallel^\dagger\overline{B}_0}\cdot\mathbf{b} + \frac{\partial F}{\partial u}\frac{\mathbf{B}^\dagger\cdot\nabla\tilde{\phi}_1^{(1)}}{B_\parallel^\dagger\overline{B}_0}}_{\text{Energy-conserving corrections}}\Big] \qquad (4)$$

$$\times\, \delta[\mathbf{x} - \mathbf{X} - \rho(\mathbf{X})]B_\parallel^\dagger d^3X d\mu\theta$$

Further simplifications can be made

- A further reduction, valid for long wavelengths, $k_{||} << k_{\perp}$ + approximations that $F_{\perp}$ Maxwellian, and inhogeneity in ϕ_0 dominates that of n_0, T_0:

$$\sum_{\alpha} \frac{\rho_{\alpha}^2}{2\lambda_{D\alpha}^2} \nabla_{\perp} \cdot (\ln N_{\alpha} \nabla_{\perp} \phi) + \nabla^2 \phi = - 4\pi e \left[\sum_{\alpha} Z_{\alpha} N_{\alpha}(\mathbf{x}, t) - n_e(\mathbf{x}, t) \right] - \sum_{\alpha} \frac{\rho_{\alpha}^2}{2\lambda_{D\alpha}^2} \frac{1}{N_{\alpha} Z_{\alpha} e} \nabla_{\perp}^2 p_{\perp\alpha}. \quad (5)$$

  - Fully nonlinear: use GK n, $P_{\perp}$ to evaluate coefficients
  - Used in TEMPEST results shown later

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Two main approaches to solution offer different advantages

- Particle-in-cell: integrate (macro) particle orbits in self-consistent fields; gather moments from particles for field source terms.
  - Particle conservation and positivity of f guaranteed for full f.
  - Implementation of particle dynamics relatively straightforward
  - Noise issues -- aggrevated by need for big density contrast and typically also by collisions
    - Solving with lots of particles maps well to massively parallel computers

Two main approaches to solution offer different advantages (cont)

- Continuum: represent f on a 4D or 5D grid (and/or use basis functions)
  - Inherently noise free
  - Can exploit fluid simulation community's experience (implicit methods, solvers, AMR, ….)
  - Accuracy issues associated with finite v-space discretization $\Rightarrow$ need many grid points?
    - Especially for large temperature contrast of edge region
    - Experience from core codes: need surprisingly low v-space resolution. Will this cary over to edge?
  - Need to explicitly handle conservation issues, positivity of f, possible numerical instability of dynamics advance.
  - Collisions smooth and so help resolution issues

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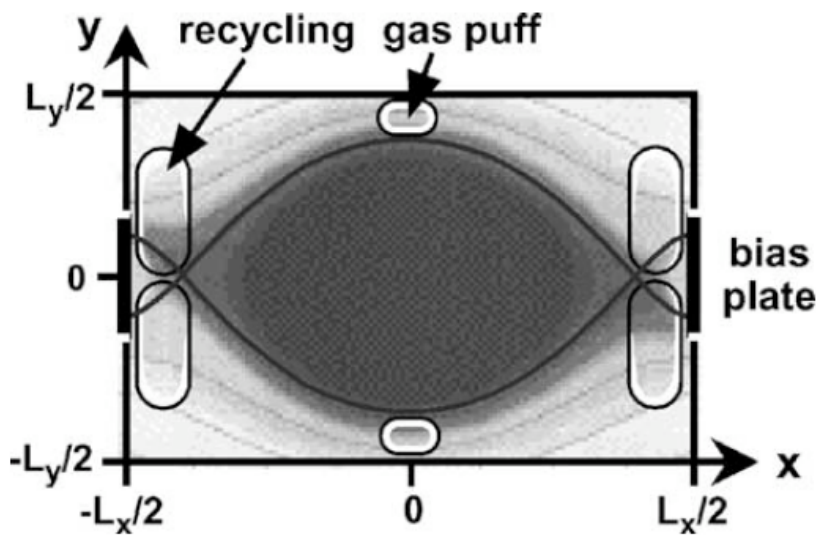
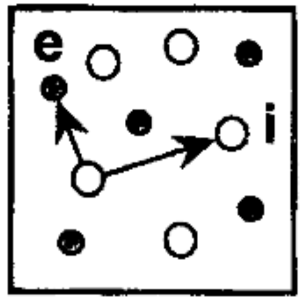
PIC-based: PARASOL (JAEA Naka; Takizuka et al)

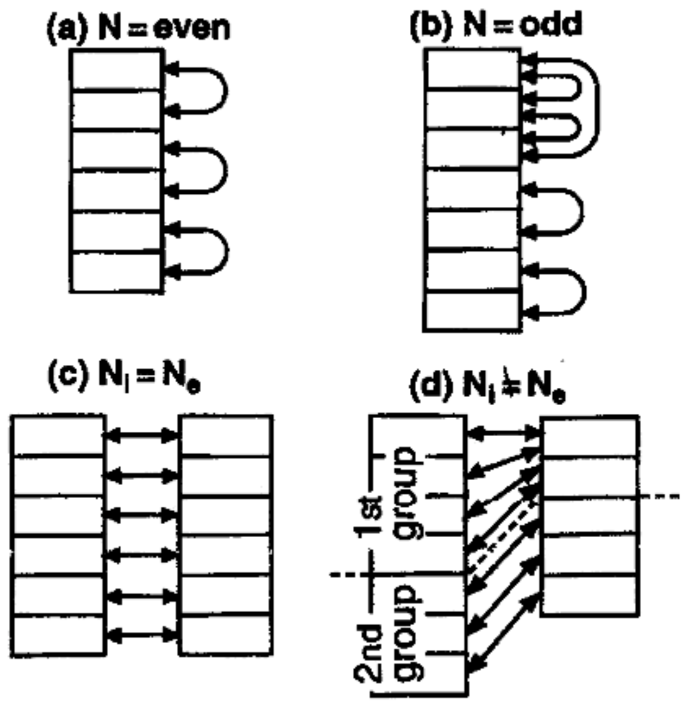
- Older 1-D model extended to 2D.
- Closest to first-principles effort:
  - Solves Vlasov-Fokker-Planck equation (1)
  - Resolves Debye sheath; no modeling required
  - Tradeoff: limited to small-size physical domains; more computationally intensive than GK
- Other attributes
  - Binary collision model (see below)
  - Slab double-null divertor configuration (or simple slab)
  - Neutrals interactions
  - Monte Carlo diffusion to model turbulent transport



PIC based: PARASOL (cont)

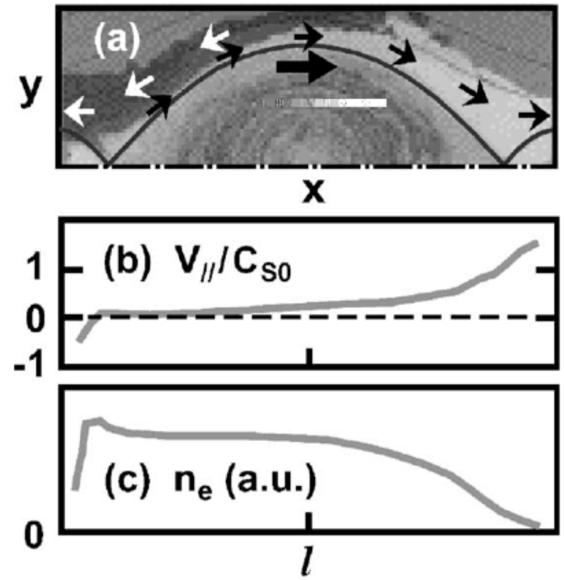
- Binary collision model (Takizuka-Abe) is used in many simulation projects
- Selects pairs within a cell
- Random scattering angle generated in center-of-mass system
- Conserves particles, momentum, energy
- Scales with # of particles

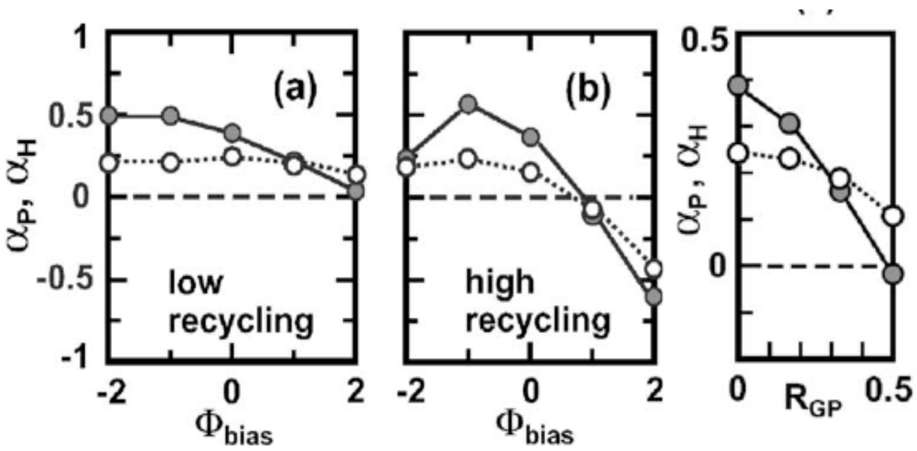




PIC based: PARASOL (cont)

- Example physics calculation: controlling flows by gas puff and biasing [JNM 313-316, 1331 (2003)]
  - Natural asymmetry of macroscopic flow velocities, atttributed to combination of ExB and diamagnetic flow
  - Can rebalance flow through either
    - relative biasing of divertor plates (induces asymmetric sheath conditions offsettinig asymmetry)
    - Gas puff: alters radial density profile and so effective diamagnetic flow





PIC-based: ASCOT/EMFIRE (Helsinki, Heikkenin)

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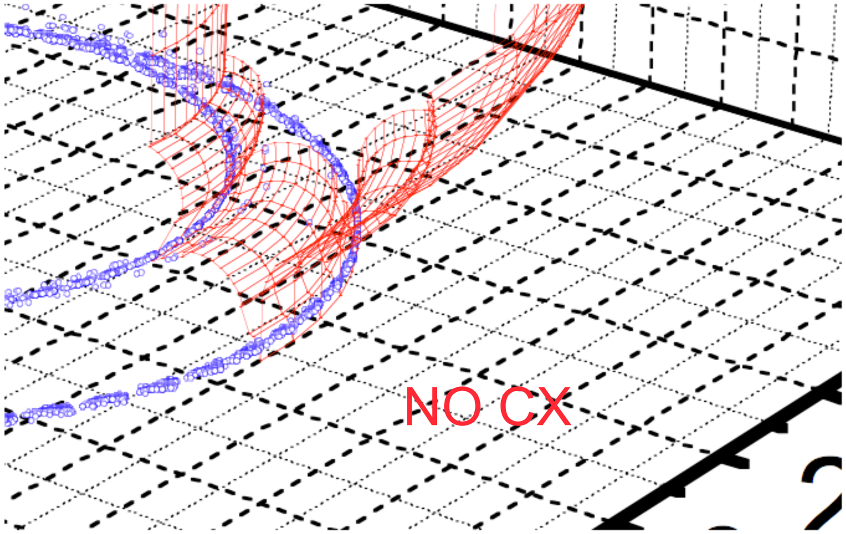
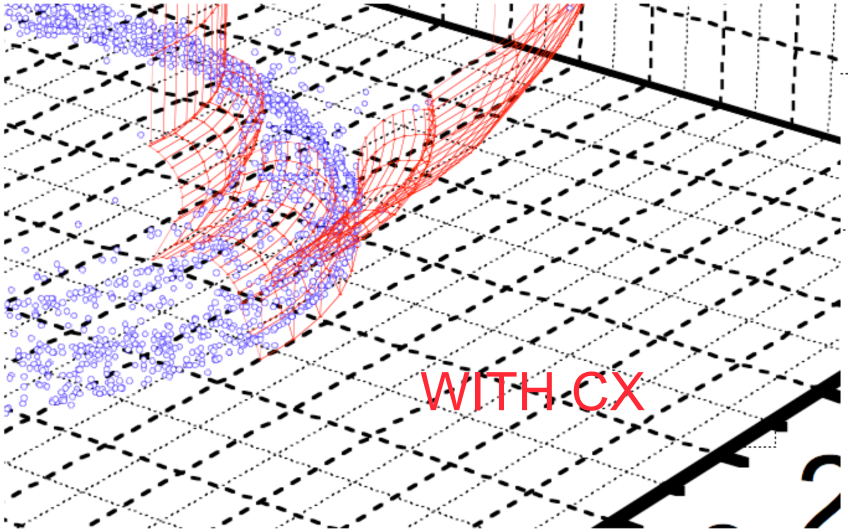
- ASCOT: 2D drift Monte-Carlo code,dating back to at least 1995 (!)
  - Flux-surface-averaged potential from current-balance relationship
    - $\partial E_r/\partial t = -(1/\alpha)\langle j_r \rangle$, $\alpha \sim \omega_p^2/\Omega_c^2$
  - Collisions: binary, or over fixed background
  - Optional ripple B field
- ELMFIRE: 3D full-f gyrokinetic
  - Based on Sosenko's Krylov-Boholiubov averaging of gyro orbits (Sosenko et al, Physica Scripta **64**, 264 (2001).)
  - Field solve: gyrokinetic-Poisson; fully nonlinear treatment of coefficients
  - Novel approach to polarization drift: CHANGE in polarization charge density at each timestep included in LHS of GK-Poisson eq. (verus full polarization charge in most treatments), and then particle positions are updated at end of step based on computed change of potential.

PIC-based: ASCOT example calculation

- Deposition of ions on ITER divertor in presence of ripple, without and with neutral charge exchange

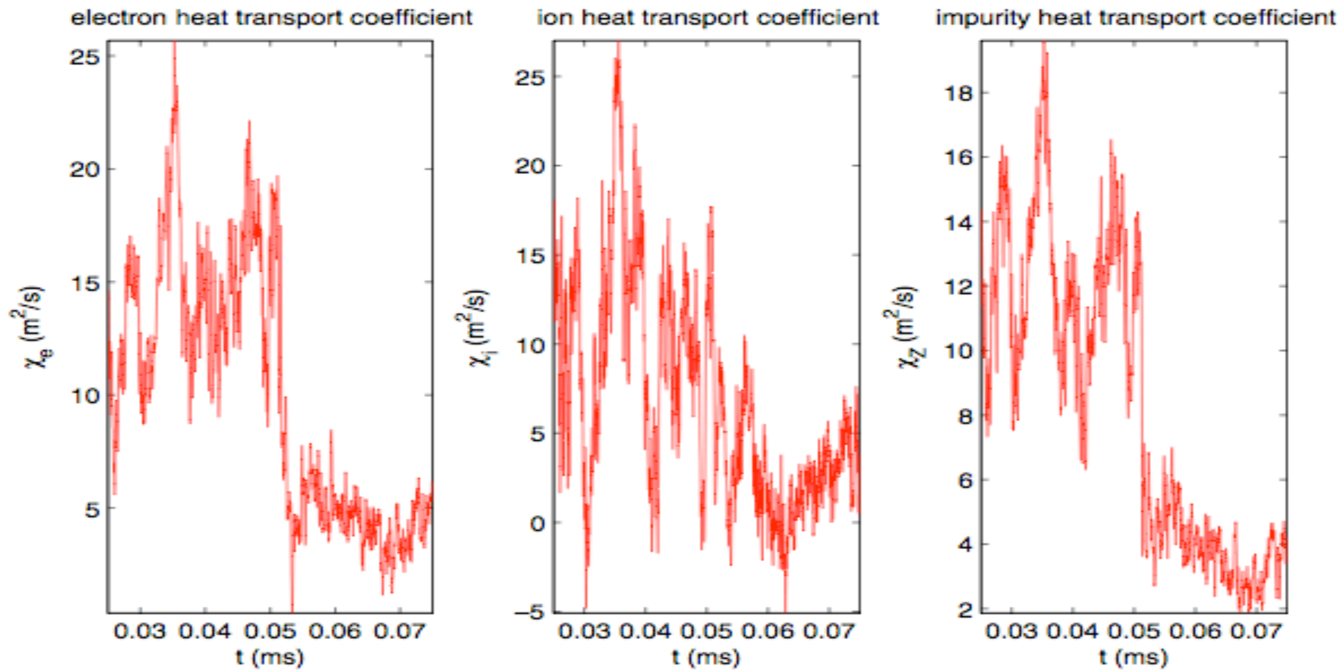




- Other recent studies
  – Particle & heat dist. of NBI-injected particles in ASDEX-U
  – Confinement of fusion alphas in JET
  – Enhanced heat/particle diffusion in JET due to ripple
  – Role of hot electrons in distribution near divertors

PIC-based: ELMFIRE example

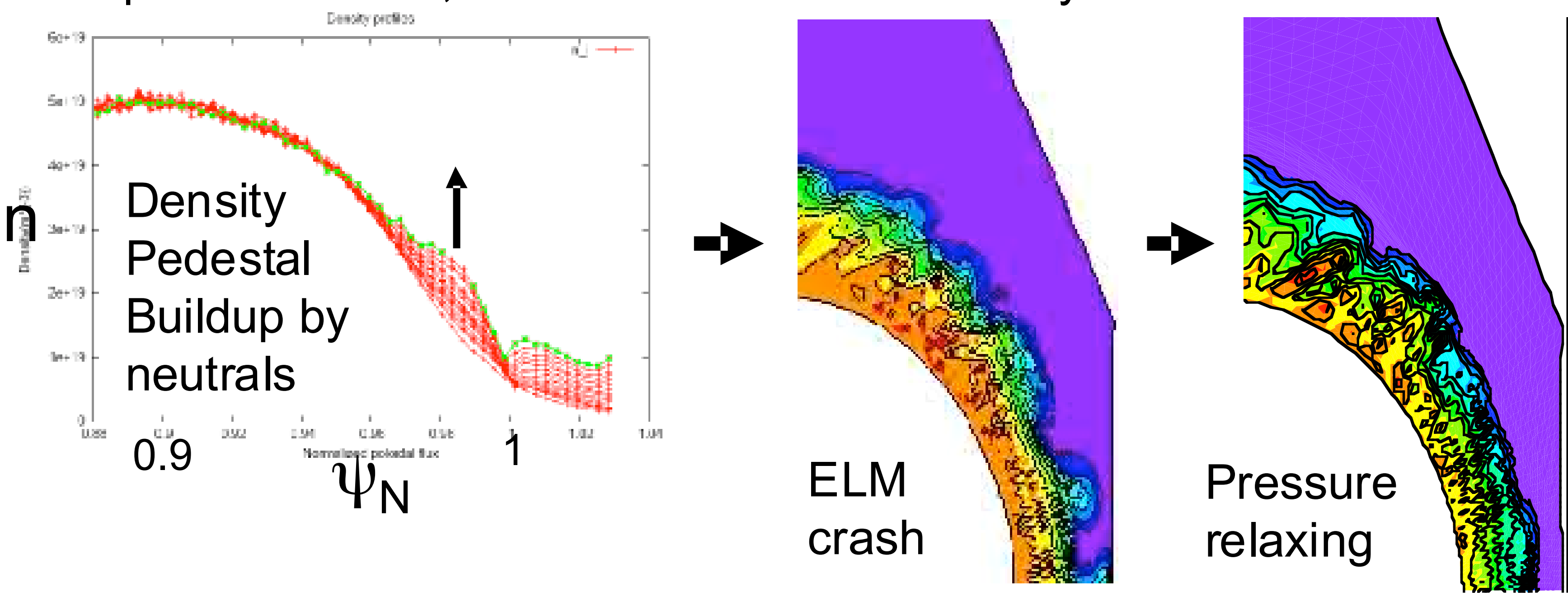
- Formation of transport barrier in FT2 tokamak, with oxygen impurity [PPCF **48**, A327 (2006)]



- Other studies:
  – Verification against Cyclone Ion Temperature-Gradient (ITG) test problem
  – Neoclassical transport in presence of developed turbulence

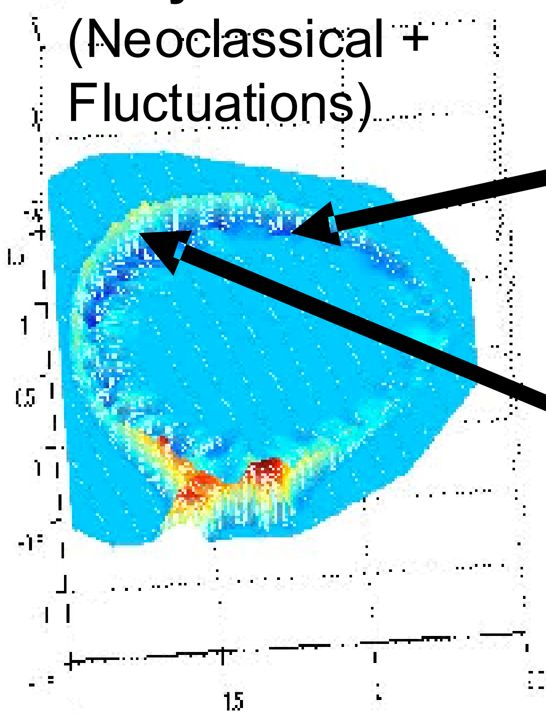
PIC-based: XGC (Center for Plasma Edge Simulation, CPES -- Chang -- a U.S. Fusion Simulation Project prototype center)

- XGC0 is a PIC (ion-electron) kinetic equilibrium evolution edge code with Monte Carlo neutral particle recycling and 3D B (5D particle motion, 1D potential solver, logical sheath)
- XGC1 is a 5D PIC electrostatic turbulence+neoclassical edge code (E&M capability later)
- XGC0 and M3D are coupled to simulate the pedestal/ELM cycle.
- XGC1 will be coupled into XGC0 for turbulence transport
- Kepler framework, with web-based user-friendly dashboard service



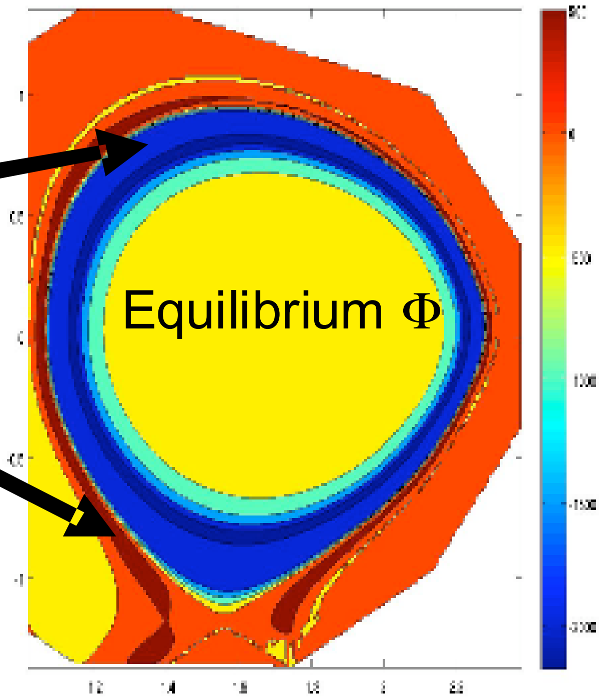
PIC-based: CPES (XGC) (cont)

Early time 3D Φ
(Neoclassical + Fluctuations)



Negative potential well in H-layer (dark blue)

Positive potential hill in scrape-off (yellow-brown)



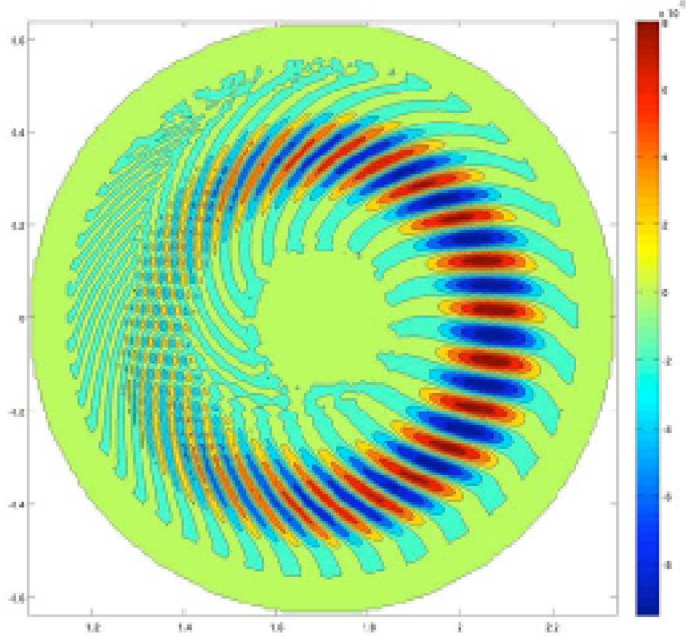
First 3D electrostatic solution across separatrix has been obtained from XGC. What fraction of the fluctuation is numerical?

Equilibrium Φ distribution has been extracted from 3D by toroidal averaging and poloidal-time smoothing

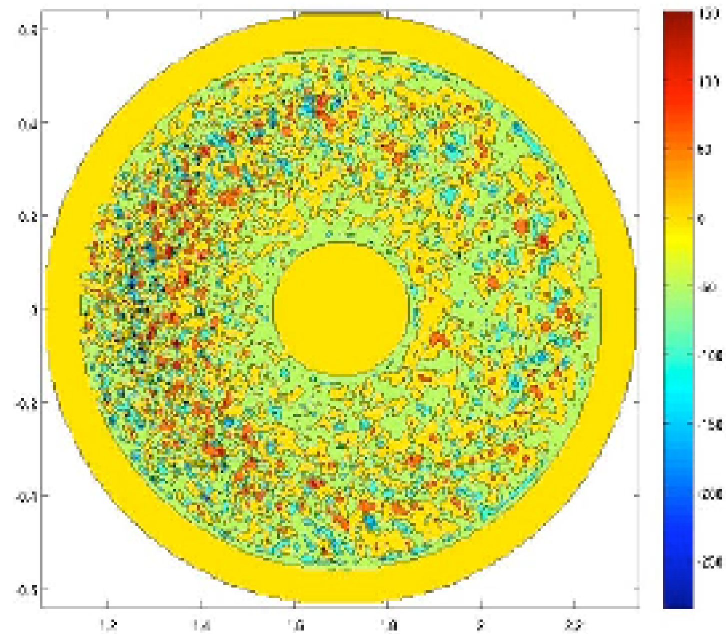
PIC-based: CPES (XGC) (cont)

Turbulence XGC is under careful verification against the well-known cyclone results.

XGC will move back to the edge turbulence afterwards..



Linear ITG growth rates have been verified.

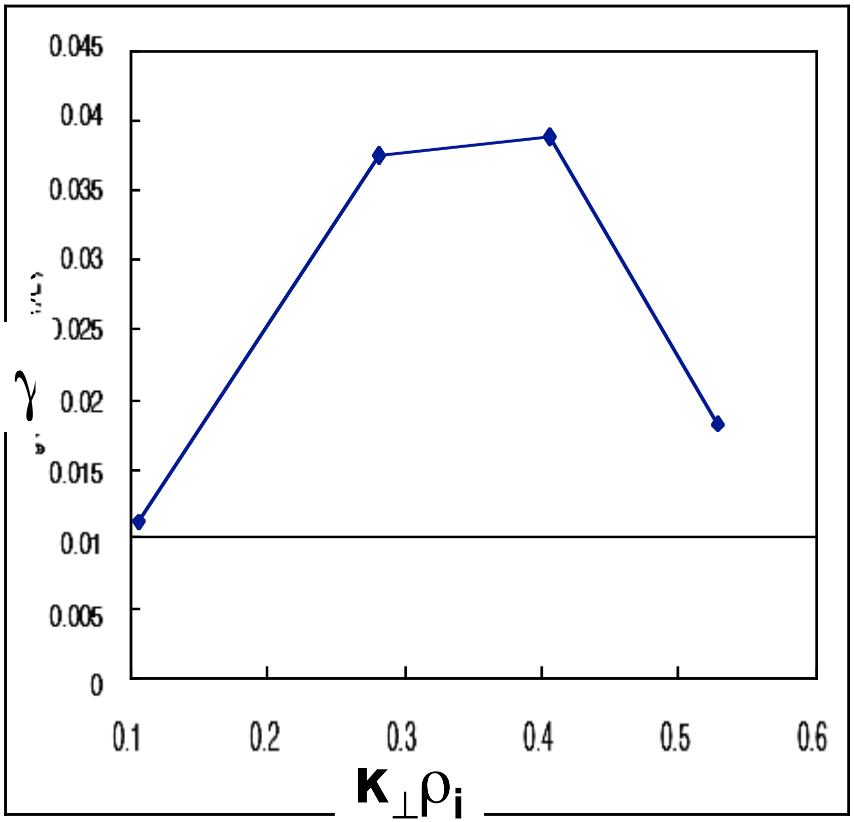


Nonlinear ITG is rigorously getting verified at the moment.

PIC-based: CPES (XGC) (cont)

Global ITG linear growth rates from XGC1 have been verified in cyclone plasma

XGC



GTC

Z. Lin and T. S. Hahm

Phys. Plasmas, Vol. 11, No. 3, March 2004

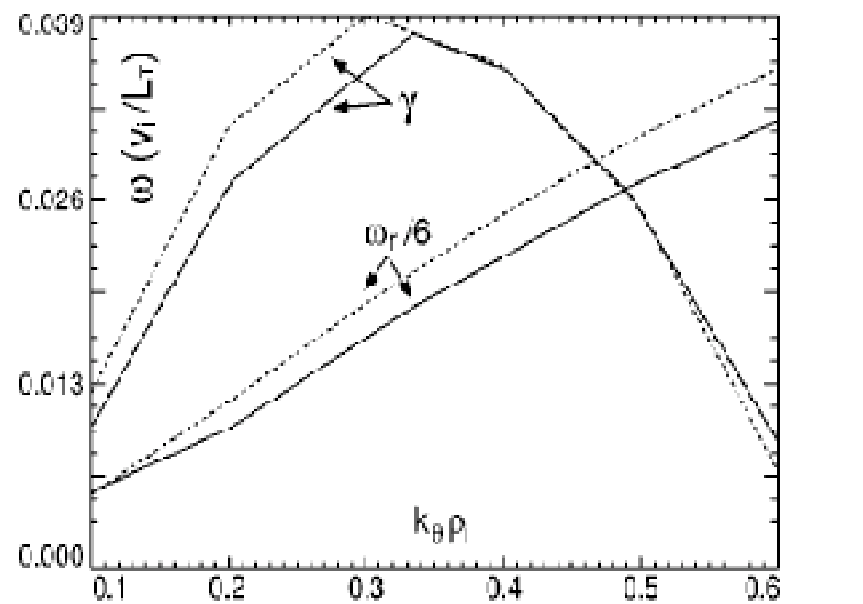


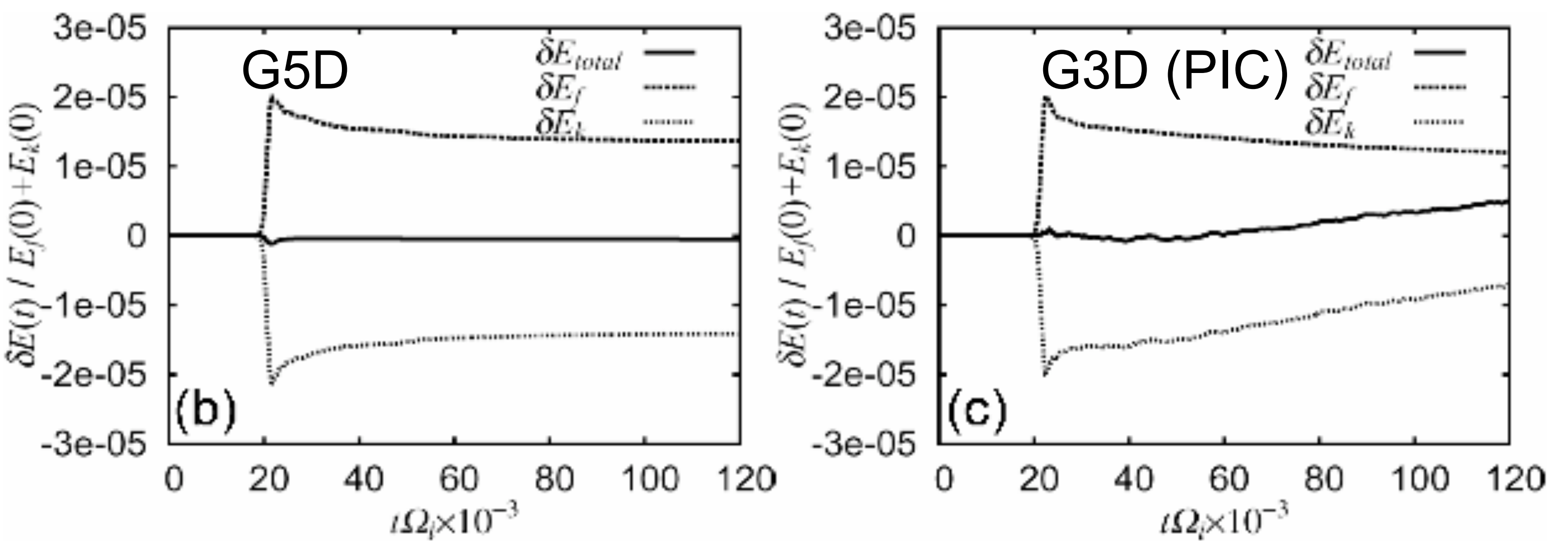
FIG. 1. Linear ITG real frequency ω_r and growth rate γ versus poloidal wave vector from GTC (solid) and FULL (dotted) calculations (upper panel),

Continuum-based: G5D (JAEA, Tokyo; Idomura)

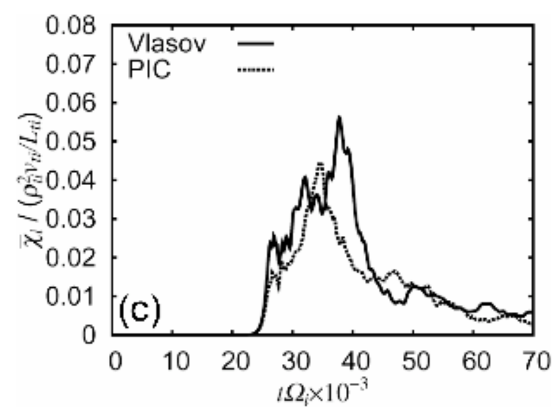
- Full-f, global code
- $v_{||}$-μ coordinates
- Presently core, but a goal includes edge transport barriers and open-field-line physics
- Conservative 2nd and 4th-order finite-difference spatial discretization schemes (Mornishari), preserves L1 and L2 norms (by using skewed representations of the streaming and drift operators)
- For now: adiabatic electrons.
- Code is under development; authors publishing tests

Continuum: G5D (cont.)

- Current testing: compare ITG simulations to G3D delta-f PIC code; slab ITG
- Shown here: 0-FLR, 4D (integrate over μ)
- PIC code has substantial numerical heating. G5D does not.



- Also studied: 5D full-gyrokinetic comparison of ITG growth and saturation versus G3D; results qualitatively similar



Continuum: FEFI (Garching, Scott)

Edge Simulation Laboratory

- FEFI = “full electrons full ions”
- A different path to complexity: going directly to electromagnetic GK, in simple (toroidal annulus) geometry and delta-f.
  - Edge-like in that non-periodic radial b.c.’s
  - $v_{||}$-μ coordinates
  - Simple (pitch-angle off fixed background) colllisions
  - Multiscale B field (const B and B’)
  - Maintains perturbations of equilibrium (axisymmetric) and associated nonlinearities, hence “edge-like”.
  - 2nd order nonlinear polarization and screening contributions to potential, for conservation

Continuum: FEFI (cont)

- Applications
  - Ion-temperature gradient turbulence in presence of imposed and self-generated flows (PPCF 2006)
  - Differences between kinetic and fluid simulations of turbulence in edge-like conditions (IAEA TM Trieste 2005)
    - Magnetic-flutter contributions always outward in kinetics;
    - low-$v_{||}$, high-μ electrons have nonadiabatic response, sufficient to produce particle flux comparable to ions

Continuum projects: ESL (U.S. multi-institutional, Cohen)

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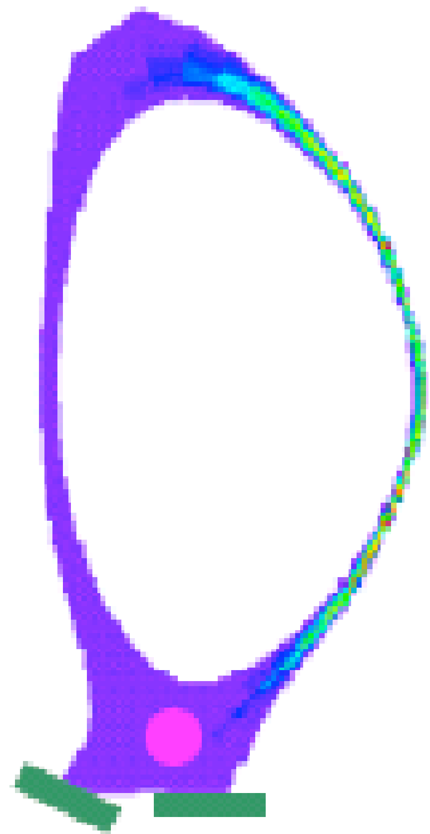
- ESL = Edge Simulation Laboratory
  - U.S. DOE (fusion and computating) base-program activity
  - Collaboration: LLNL, GA, UCSD, LBNL, CompX, Lodestar, PPPL. Others welcome.
- Present projects
  - TEMPEST code (outgrowth of LLNL LDRD project; full geometry, full-f, E-μ finite difference.)
  - EGK: prototyping code, $v_{||}$-μ, simple geometry; finite difference; presently linear
  - Next generation: high-order finite volume, fully conservative, $v_{||}$-μ, full geometry (construction begun)

Continuum projects: ESL -- TEMPEST CODE

- 5D ($\psi,\theta,\zeta,E_0,\mu$); most results here 4D
  - E_0-μ choice for accurate || streaming
- Full f, but also δf option
- Geometry options:
  - Shifted circle core
  - Full single-null diverted, closed-flux-surface + SOL
- Implicit backward-differencing time advance; Newton-Krylov iteration
- 4th-order upwinded finite-difference spatial discretization, and Weno
- Low-order finite-volume discretization for collisions
- Collision options
  - Krook
  - Lorentz with full v dependence
  - Full collision op. with test-particle or fully nonlinear Rosenbluth potentials



Continuum projects: ESL -- EGK CODE

- EGK is a "rapid-prototype code" to explore physics and algorithm issues associated with edge simulation
- Currently:
  - δf
  - $v_{||}$-μ coordinates
  - Lorentz collisions
  - Electrostatic
  - Adiabatic or gyrokinetic electrons
- Themes for exploration:
  - Tradeoffs of $v_{||}$-μ representation (vs. E-μ for TEMPEST, E_k, $v_{||}/v$)
    - Plusses: simple volume element; simple representation of parallel nonlinearity
    - Minuses: $\mu \, \partial B/\partial s \, \partial f/\partial v_{||}$ trapping term bridging passing-trapped boundary can be numerically challenging
  - Unified treatment of neoclassical transport and turbulence

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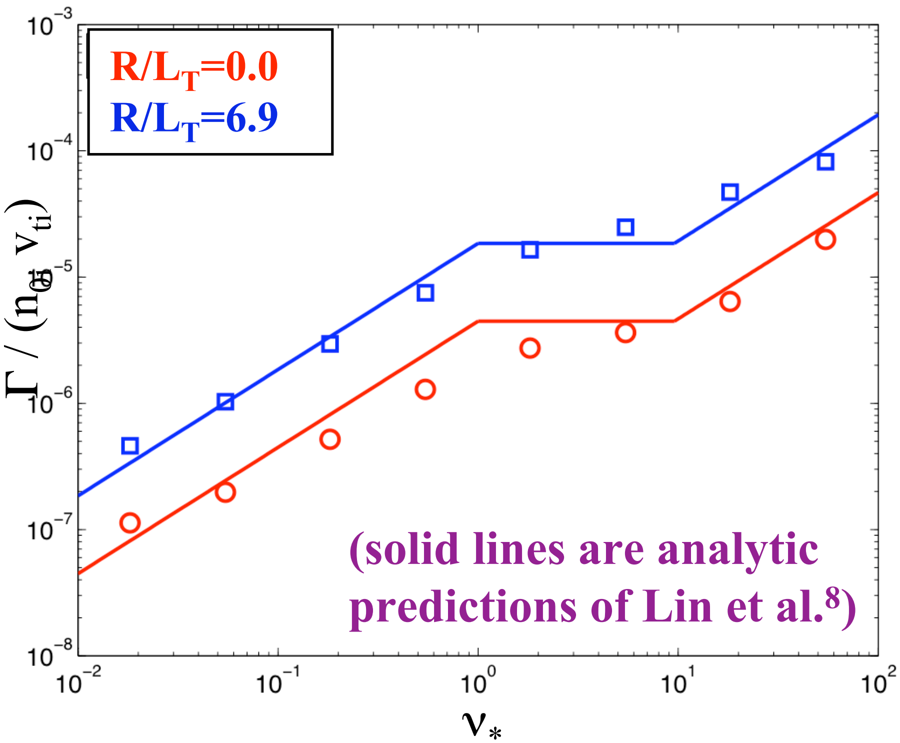
Radially local EGK has been benchmarked against neoclassical results

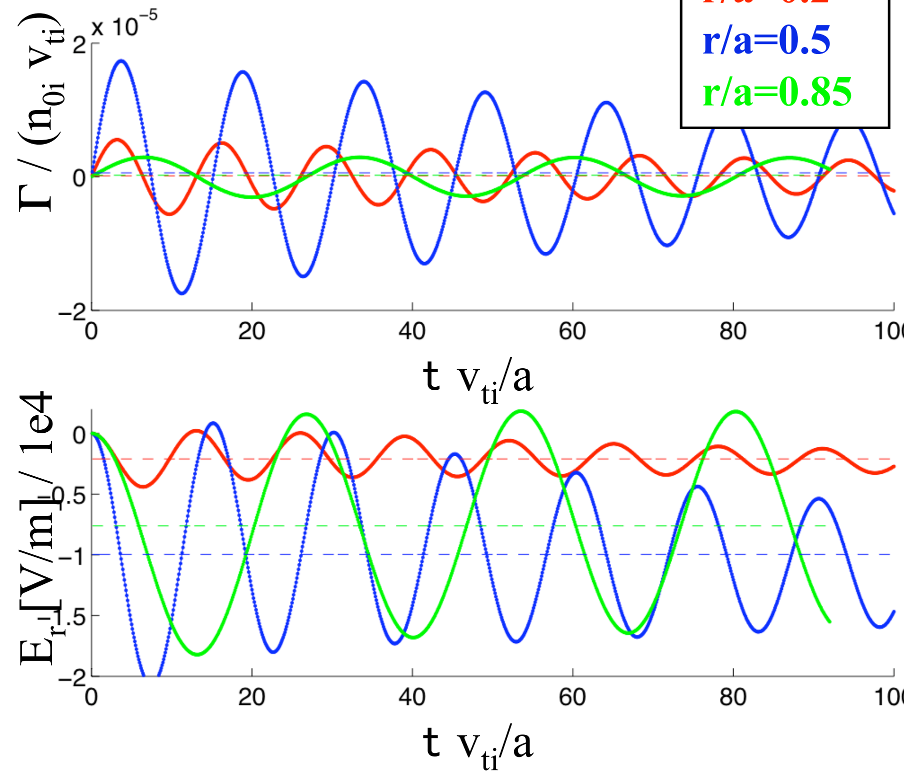
E_r^0=0



r/R=0.18 ρ/R=0.001
q=1.388 R/L_n=2.2

Including E_r^0 (vorticity eqn coupling)

Agrees with Satake et al.[7] fig. 4



R/a=4.0 ρ/a=0.0039 n, T vary
q=3.0 $\nu/v_{ti}/a$=0.1 R/L_n, R/L_T vary

8) Phys. Plasmas **2**, 2975 (1995)

Unlike lowest order problem, radial particle flux with poloidal Φ variation included is not exactly zero.

Operating on kinetic eqn with $\left\langle \int d^3v \frac{v_\parallel}{B} \cdots \right\rangle$ yields (in steady state):

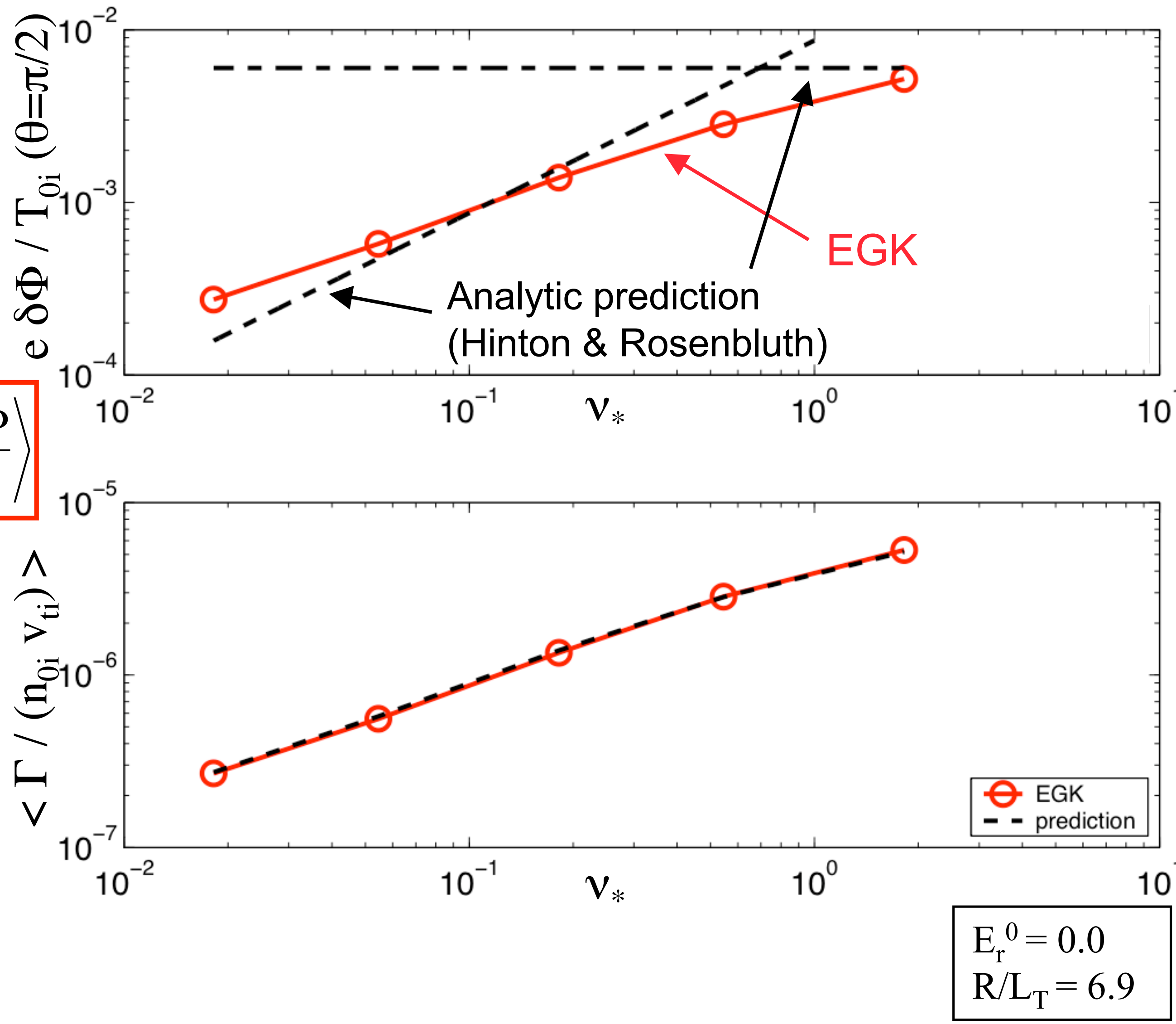
$$\boxed{\left\langle \frac{\Gamma}{n_{0i} v_{ti}} \right\rangle = \frac{1}{\varepsilon} \frac{\rho_0}{R} \frac{e}{T_{oi}} \left\langle \frac{B_0}{B} \frac{\partial \delta\Phi}{\partial \theta} \right\rangle}$$

Using that

$\delta\Phi(\theta)$=Csin(θ):

$$\left\langle \frac{\Gamma}{n_{0i} v_{ti}} \right\rangle = \frac{\rho_0}{R} \frac{e}{T_{oi}} C$$

(still small)



Summary of EGK Results

Edge Simulation Laboratory

Linear Gyrokinetics:

EGK solves linear $\delta f\,(r,\theta,k_y,\mu,v_{||})$ GK eqns in the ES limit, including GK electrons and trapped particle dynamics.

- Successful benchmarks of ITG/TEM linear drift wave physics & collisionless damping of zonal flows completed.
- Velocity space dissipation algorithms for $(\mu,v_{||})$ explored. Find that a careful numerical treatment of the trapping term is needed.

Neoclassical Transport:

EGK solves linear δf drift kinetics with neoclassical driver using radially local limit + pitch angle scattering.

- Successful benchmarks of E_r neglecting the poloidal variation of Φ and coupling with the vorticity constraint eqn. have been completed.
- New extended studies including $\Phi(\theta)$ and kinetic electrons indicate that the poloidal variation is weak and does not significantly affect the ion dynamics, but does enhance the electron heat flux. Agrees qualitatively with analytic neoclassical theory.

Next Studies: Unified Simulations of Drift Wave Turbulence and Neoclassical Transport

TEMPEST solves GK equations on E_0-μ grid

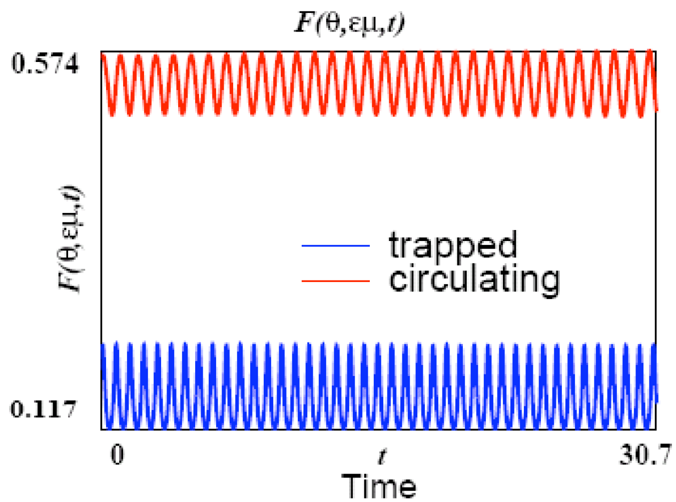
$$
\begin{aligned}
\frac{\partial F_\alpha}{\partial t} &+ \bar{\mathbf{v}}_{\rm d}\cdot\frac{\partial F_\alpha}{\partial \bar{\mathbf{x}}_\perp} + (\bar{v}_{\|\alpha} + v_{Banos})\mathbf{b}\cdot\frac{\partial F_\alpha}{\partial \bar{\mathbf{x}}} \\
&+ \left[q\frac{\partial\langle\Phi^0\rangle}{\partial t} + \bar{\mu}\frac{\partial B}{\partial t} - \frac{B}{B^*}\bar{v}_\| q\frac{\partial\langle\delta\phi\rangle}{\partial s} - \mathbf{v}_{\rm d}^0\cdot(q\bar{\nabla}\langle\delta\phi\rangle)\right]\frac{\partial F_\alpha}{\partial E_0} \\
&= C(F_\alpha, F_\alpha), \\
\bar{\mathbf{v}}_{\rm d} &= \frac{c\mathbf{b}}{qB_\|^*}\times\left(q\bar{\nabla}\langle\Phi\rangle + \bar{\mu}\bar{\nabla}B\right) + \bar{v}_\|^2\frac{M_\alpha c}{qB_\|^*}(\bar{\nabla}\times\mathbf{b}). \\
\bar{\mathbf{v}}_{\rm d}^0 &= \frac{c\mathbf{b}}{qB_\|^*}\times\left(q\bar{\nabla}\langle\Phi^0\rangle + \bar{\mu}\bar{\nabla}B\right) + \bar{v}_\|^2\frac{M_\alpha c}{qB_\|^*}(\bar{\nabla}\times\mathbf{b}). \\
\bar{v}_\| &= \pm\sqrt{\frac{2}{M_\alpha}(E_0 - \bar{\mu}B - q\langle\Phi^0\rangle)}, \\
v_{Banos} &= \frac{\mu c}{q}(\mathbf{b}\cdot\bar{\nabla}\times\mathbf{b}), \\
B_{\|\alpha}^* &\equiv B\left[1 + \frac{\mathbf{b}}{\Omega_{c\alpha}}\cdot(v_\|\bar{\nabla}\times\mathbf{b})\right], \Omega_{c\alpha} = \frac{qB}{M_\alpha c}, \mu = \frac{\mathrm{M}_\alpha \mathrm{v}_\perp^2}{2\mathrm{B}}, \\
\langle\delta\phi\rangle &= \langle\Phi\rangle - \langle\Phi^0\rangle.
\end{aligned}
$$

- **The field is split into two parts: Φ^0 and $\delta\phi$; $E_0=mv^2/2+q\Phi_0$;**
- **E_0xB flow terms and slow variation Φ^0 from Qin's formulation will be added.**
- **Long-wavelength GK-Poisson eq. described earlier used.**

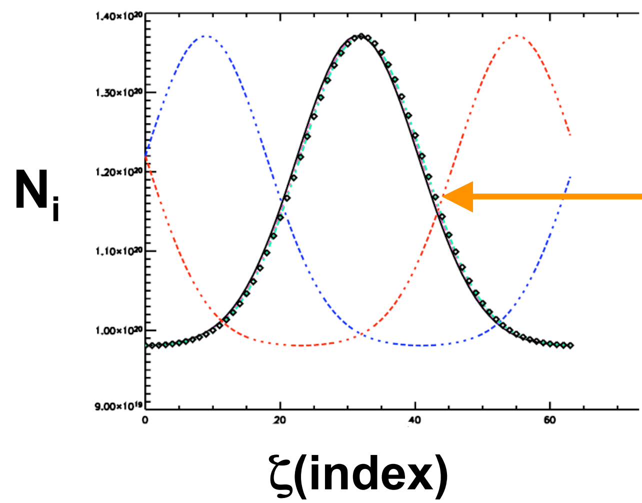
E_0-μ and high-order discretization buys us good advection

- No issue of zero-order operators spanning trapped-passing boundary

parallel

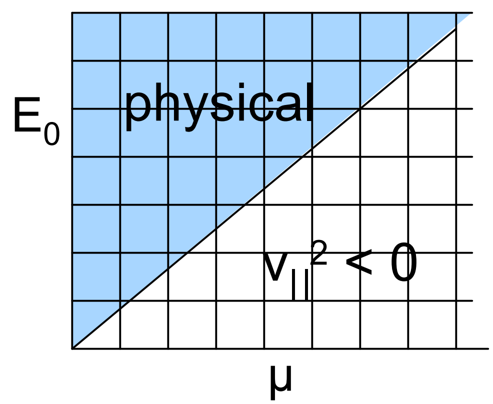


toroidal



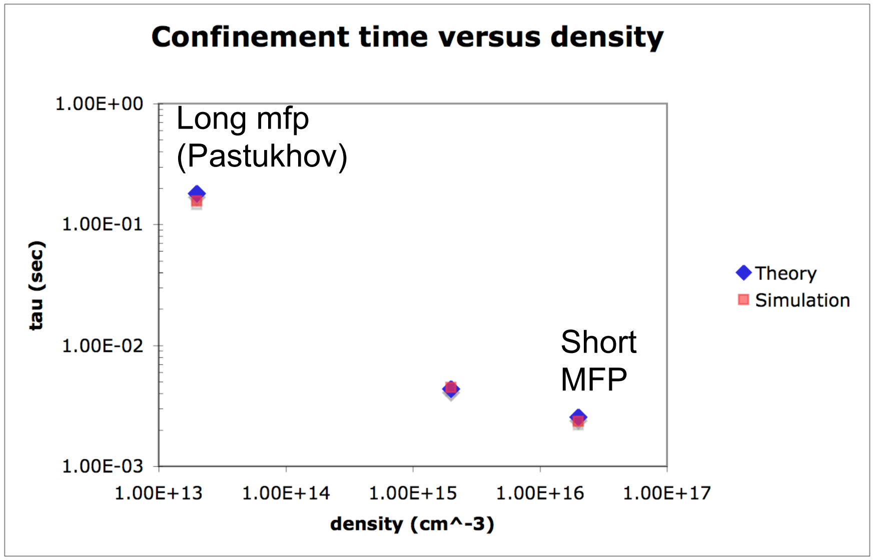
t=0, t=1st cycle and t=14th cycles overlap, Nz=64

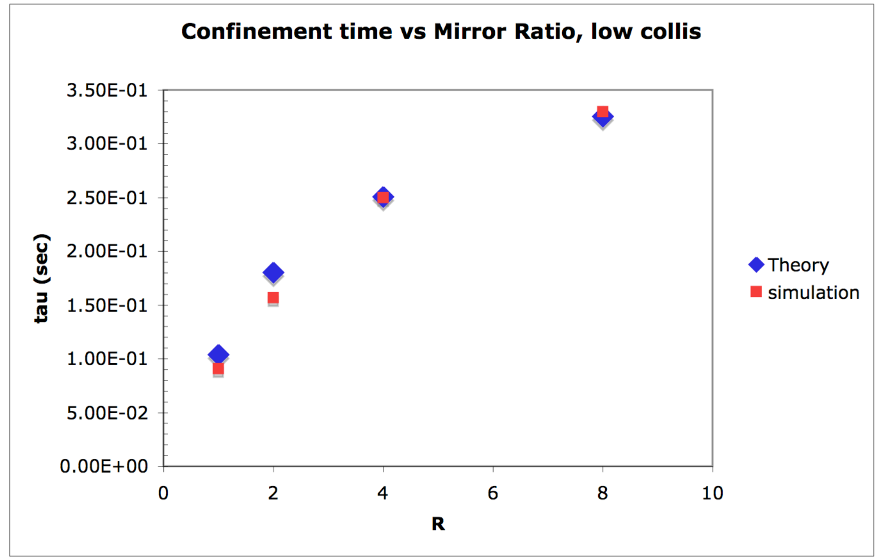
- But at a cost in complexity:
  - +, - $v_{||}$ sheets
  - Cut-cell boundaries in E_0-μ

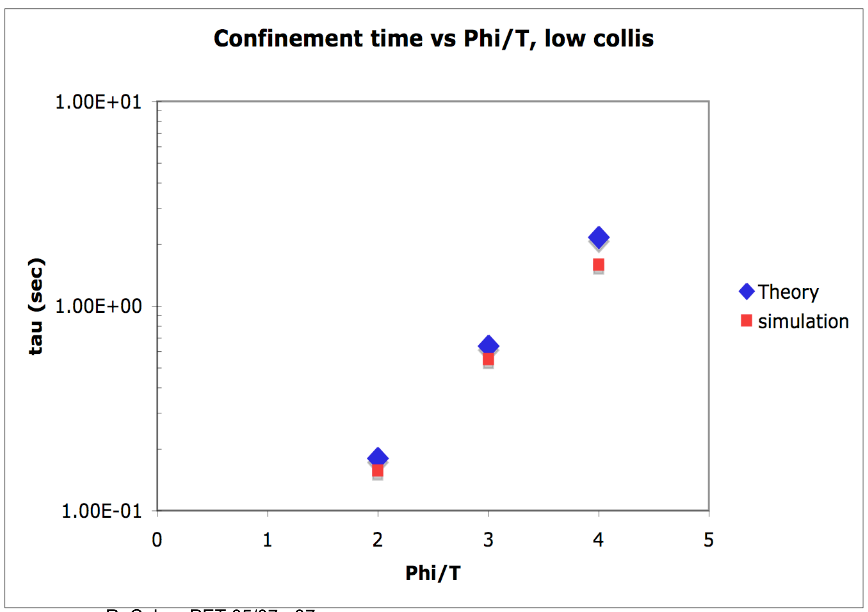


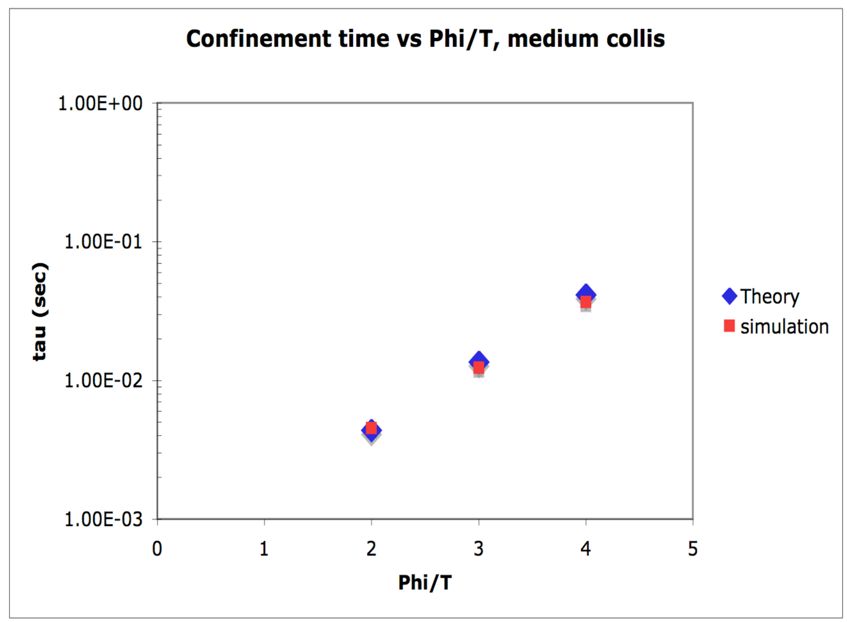
1D-2V: TEMPEST recovers theoretical endloss results with modest v-space resolution (linearized collisions)

edge simulation laboratory





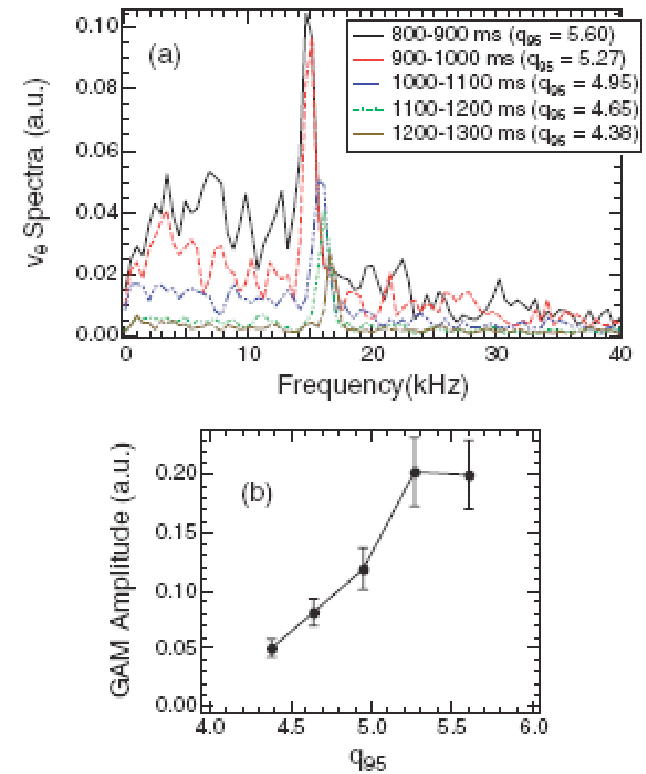




TEMPEST has been tested by simulating GAMs

- Geodesic acoustic modes (GAMs): a coherent poloidal flow oscillation
- Why we are interested:
  - A good test problem
  - Clearly identified experimentally
  - May dominate in edge
  - GAM and zonal flows are driven by turbulence and act to regulate it by time-varying ExB flow shear decorrelation
- TEMPEST setup:
  - Drift-kinetic ions, Boltzmann electrons
  - Periodic radial b.c.'s
  - Homogeneous plasma with initial δn_i

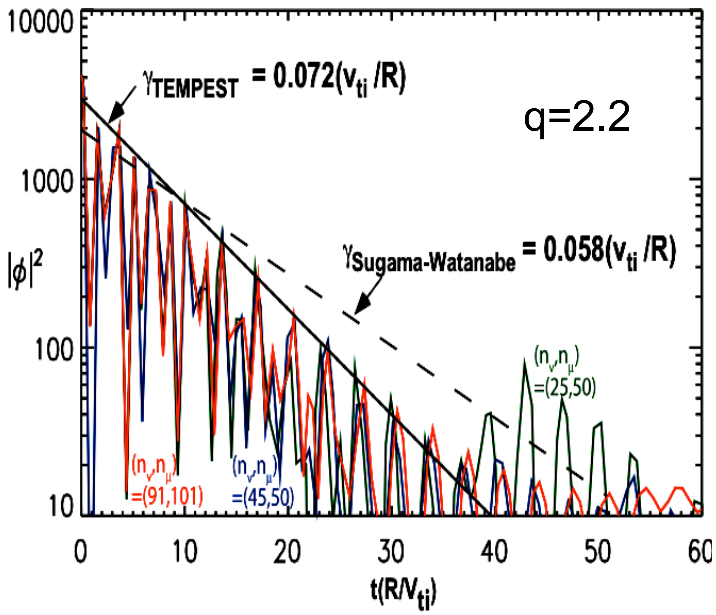
$$\delta n_i = \delta n_0 \sin(2\pi r/L_r)$$

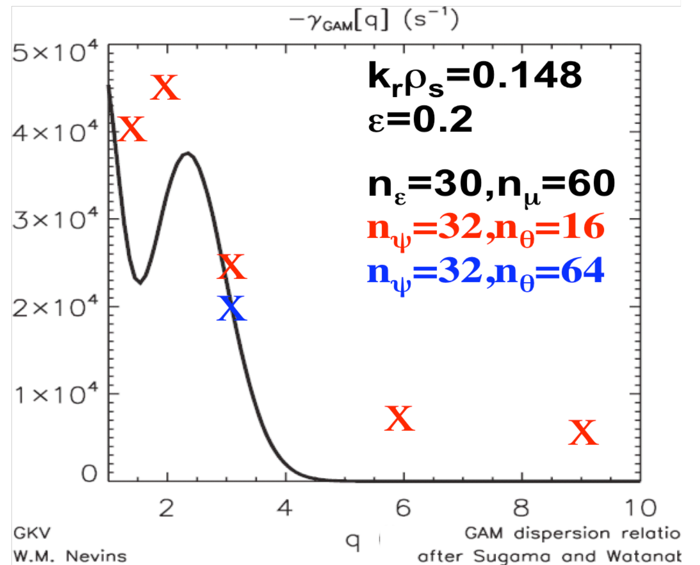


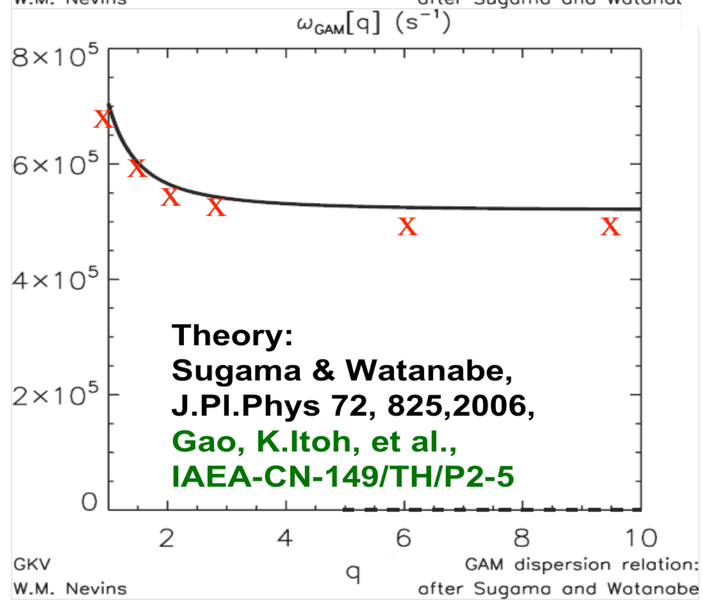
DIII-D BES GAM expt.
Mckee, PPCF, 48, s123(2006)

Tempest GAM simulations agree reasonably well with new large-drift-orbit theory (Sugama-Watanabe)

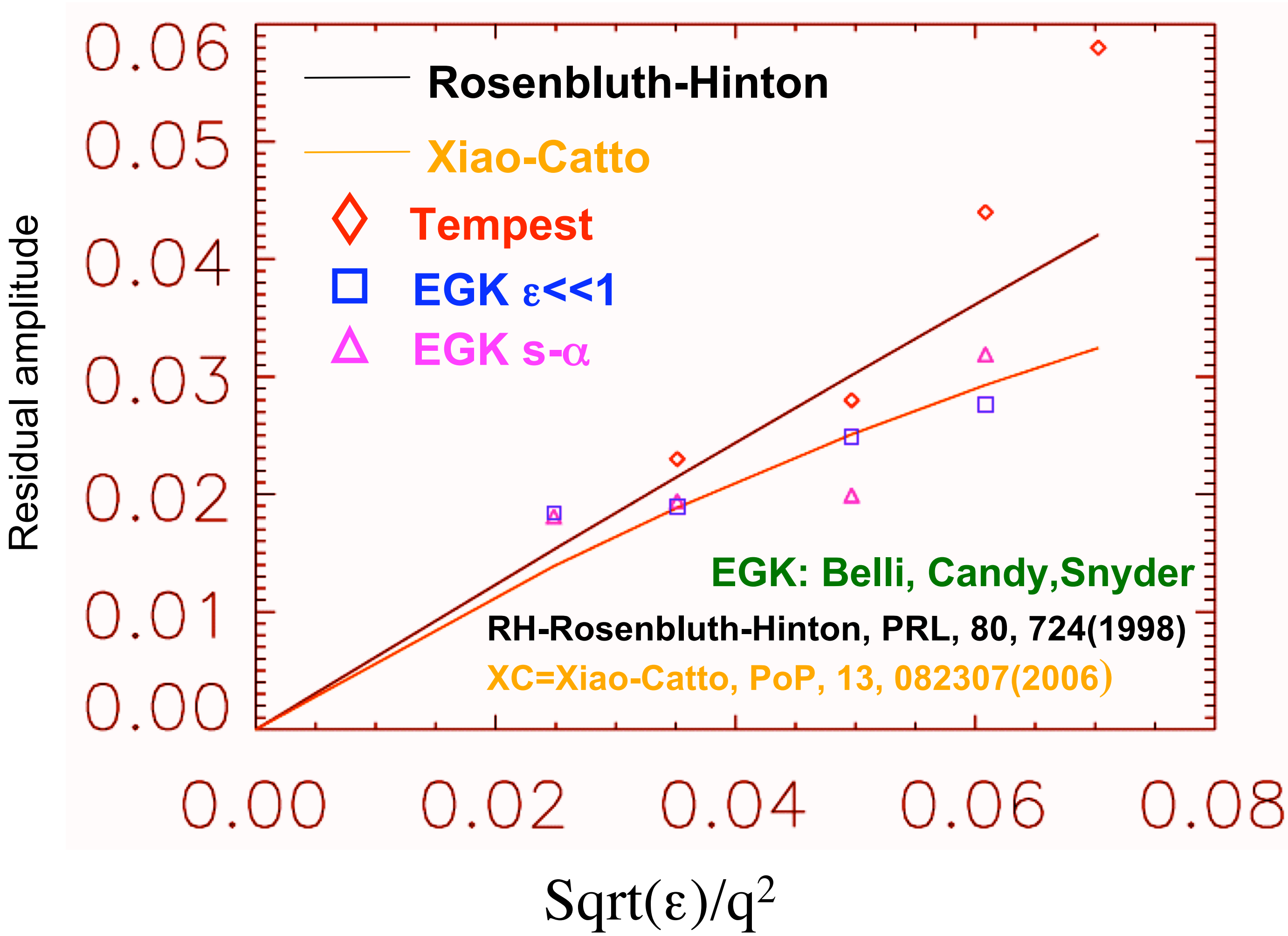
edge simulation laboratory







ε scan: Tempest and EGK GAM simulations agree with each other and theory

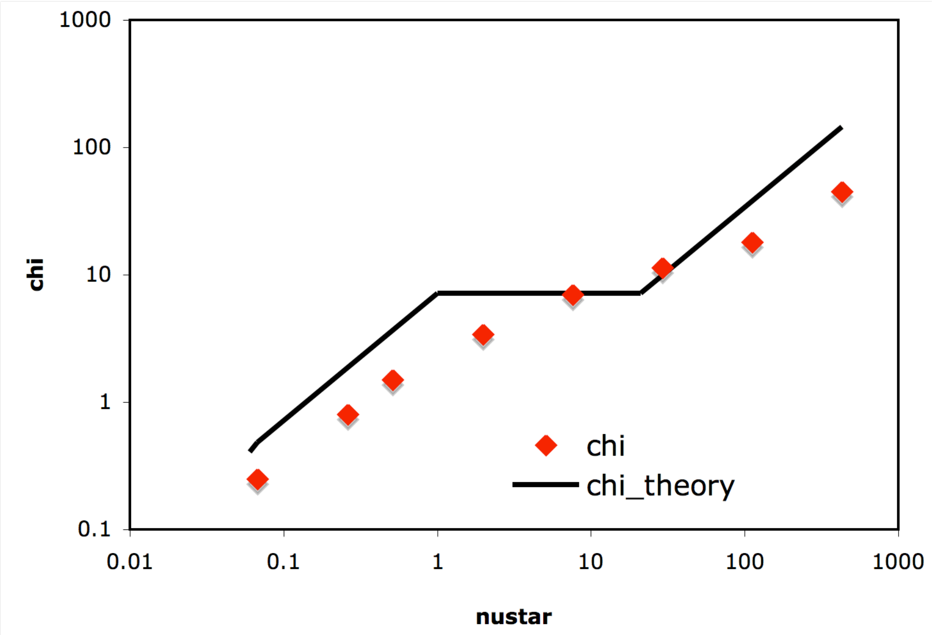


TEMPEST Neoclassical tests

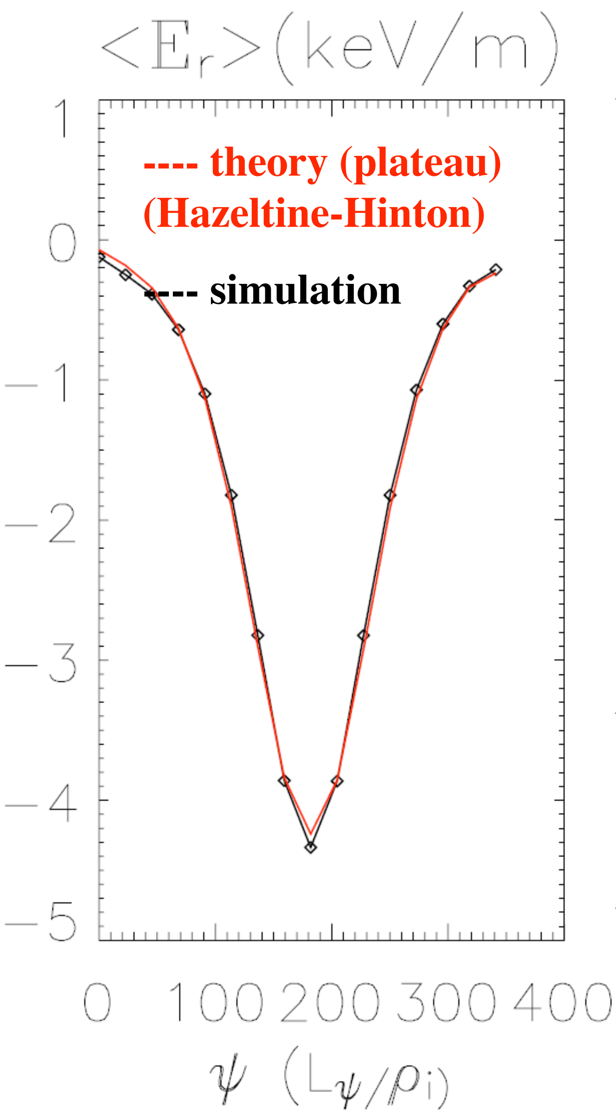
- Tests done using Krook and Lorentz models
- Tests done with both available geometries (circular ring and divertor)
- FULL f (not delta-f), and not radially local
- Steady-state problem definition:
  - specify f=Maxwellian with prescribed n, T on inner and outer boundaries where drift is into domain
  - Specify no returning flux at divertor plates for divertor runs

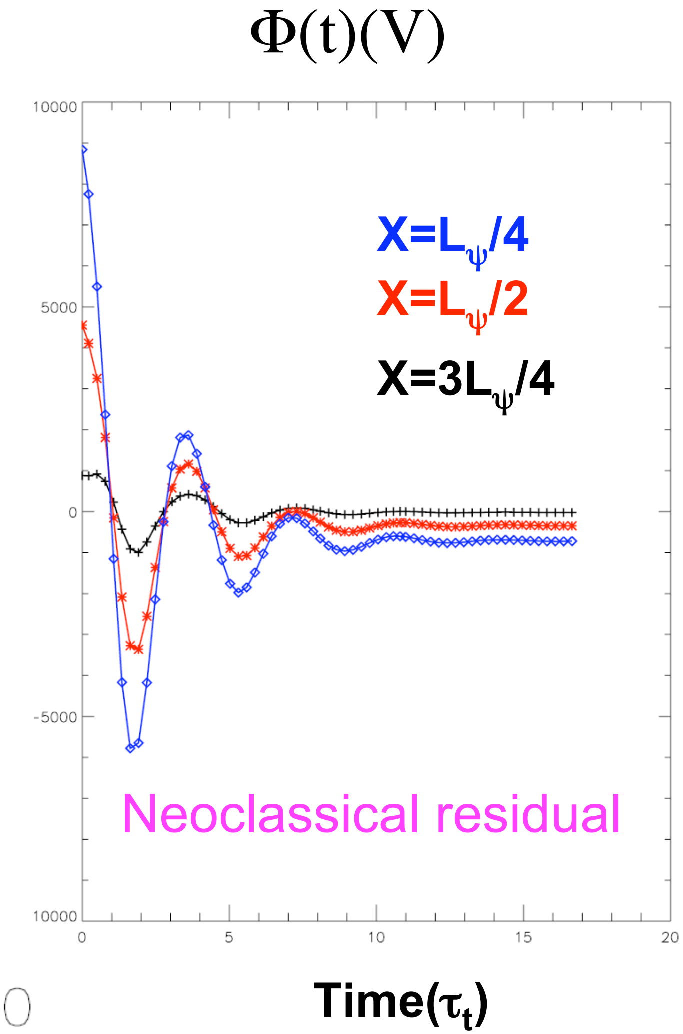
Tempest ν^* scan

- Circular geometry, annulus, weak gradients (10% n and T variation over annulus)
- Lorentz collisions, full-v dependence
- No E field
- Npol*Nrad*NE0*Nμ = 30*36*25*44
- Compare to expressions derived by Lin
  - Lin: derived for const ν.
  - Comparison done with ν from NRL tables temperature isotropization

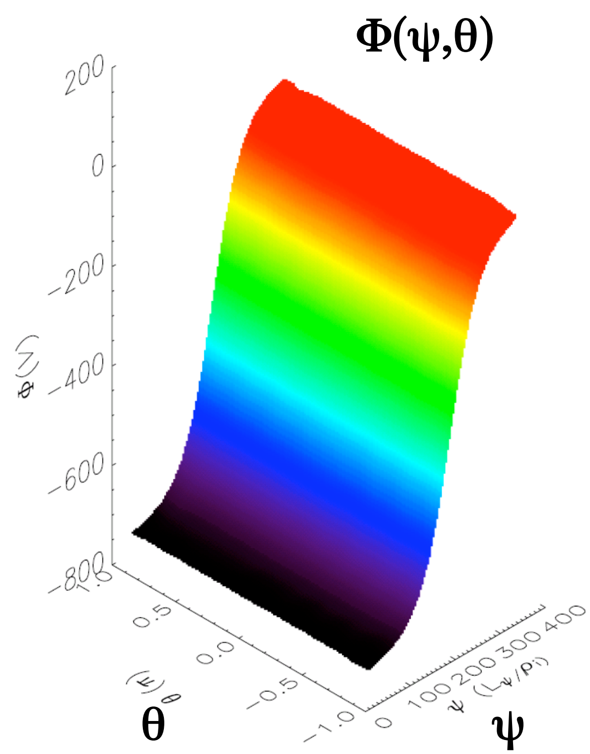


Tempest neoclassical potential solution reproduces theory





- ✓Er is generated due to neoclassical polarization
- ✓Krook collisions
- ✓True steady state

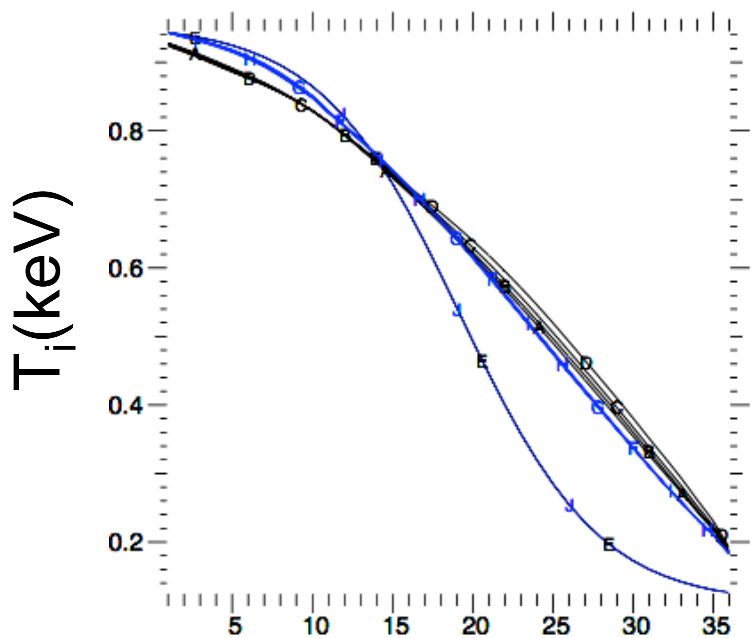


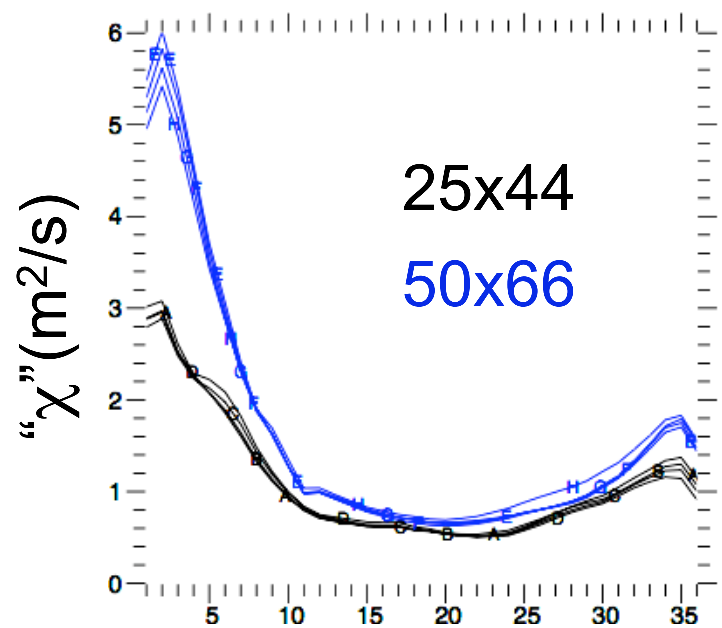
TEMPEST Comparison with XGC: core slice

- Core annulus from ψ_N = 0.4 to 0.6, DIII-D
- Edge-like, steep T and n profiles: T_i varies from 1 keV to 100 eV; n varies from 5e13 to 5e12.
- Lorentz colllisions, no potential
- Caveats:
  - TEMPEST run with circular flux surfaces, and collision frequency evaluated with n and T from initial profiles
  - XGC run with EFIT flux surfaces, n and T for collision frequency updated occasionally
  - Different boundary conditions
    - XGC continues colllisionless orbits at boundaries
    - TEMPEST has prescribed f for inward v_d at boundaries

Convergence w.r.t. v-space resolution

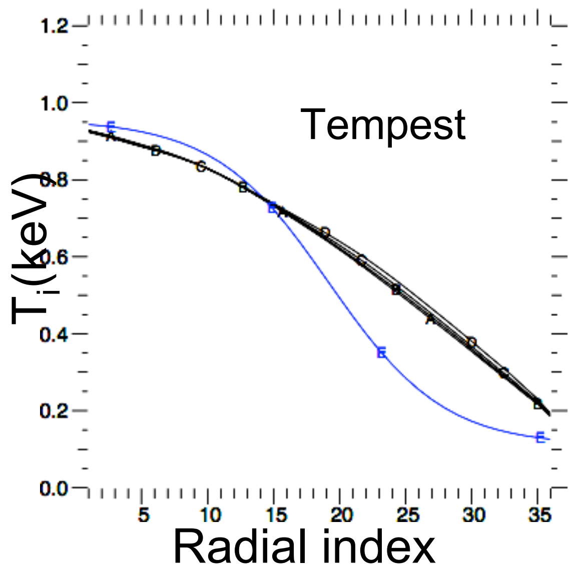
- We were concerned that our relatively coarse v-space grid would be a problem at low-temperature end of simulation
- Comparing runs at different resolutions suggests that the convergence is quite good within interior of domain.

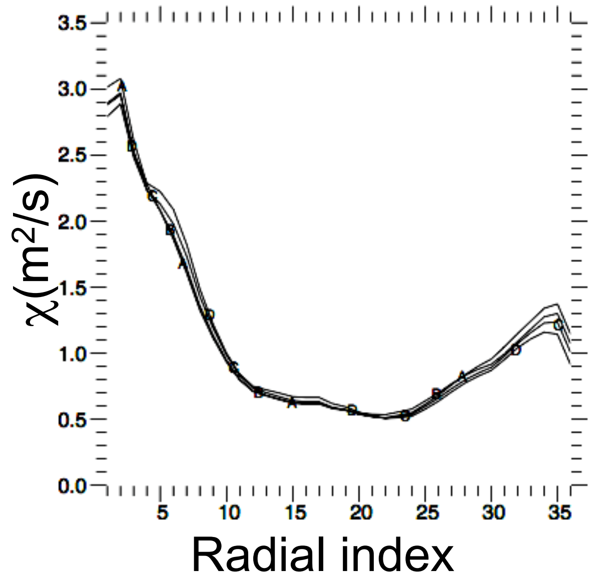


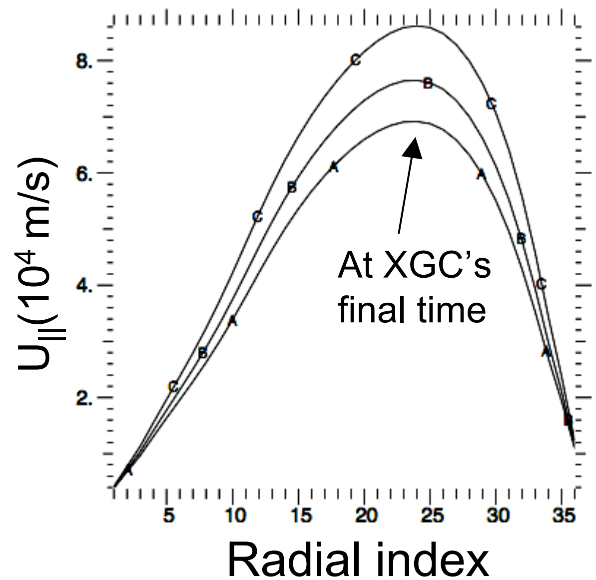


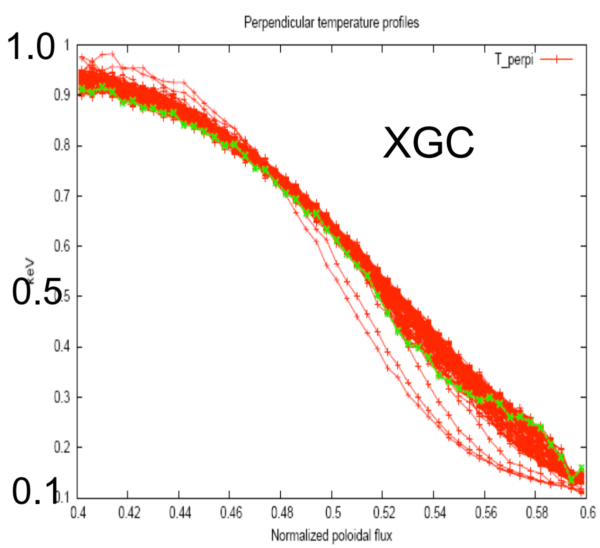
TEMPEST-XGC circular comparison: reasonable agreement

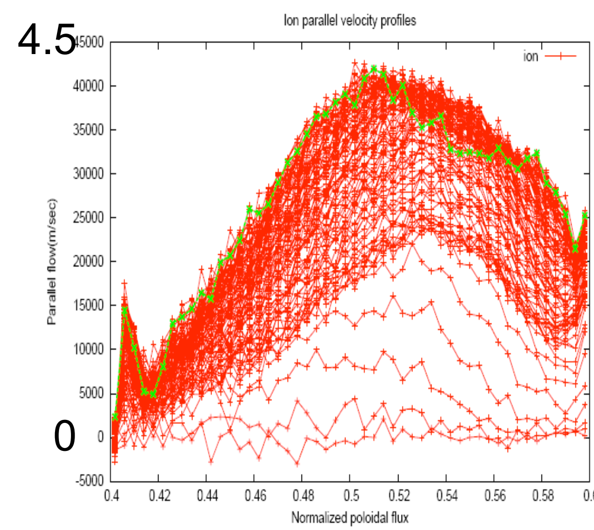
Edge Simulation Laboratory











Tempest Comparison with XGC: divertor NC simulation

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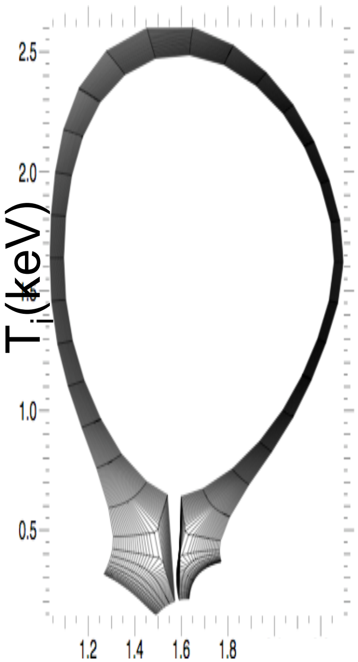
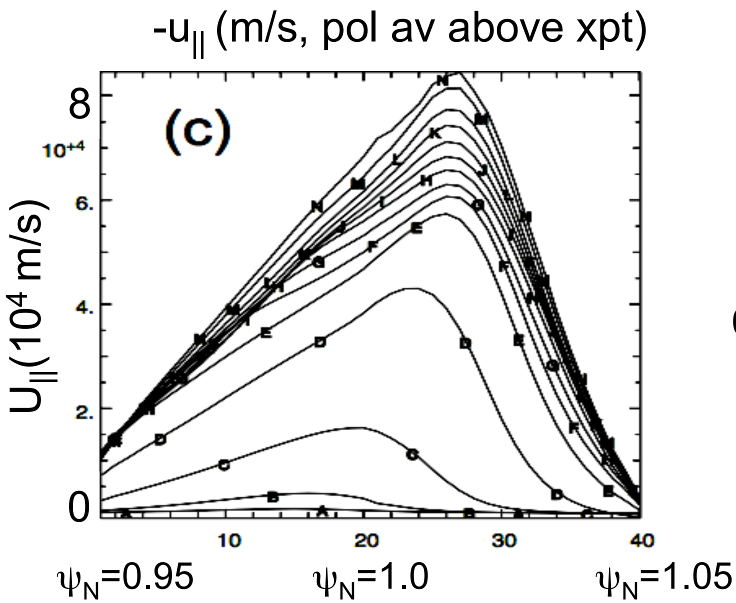
simulation
aboratory

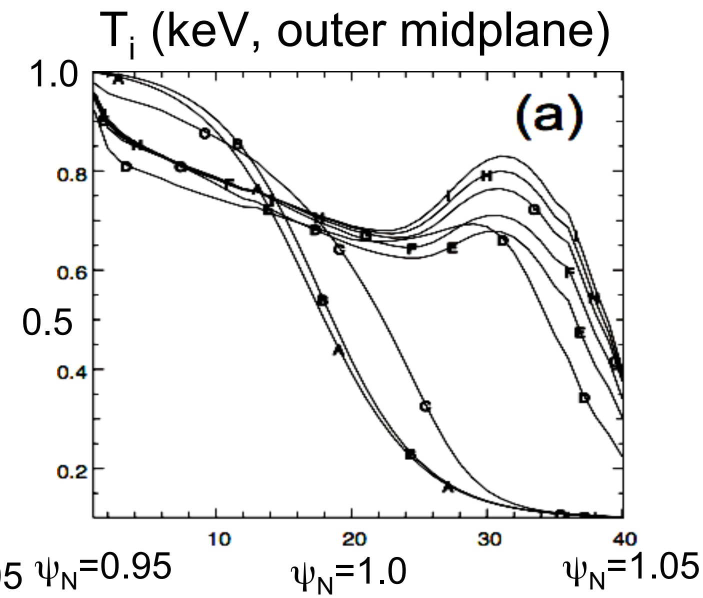
- Simulations based on common EFIT files (DIIID #096333)
- Tanh initial T_i and n radial profiles, centered at $\psi_N = 0.99$, half width 0.02; $T_{i,max} = 1$ keV, $n_{i,max} = 0.5 \times 10^{14}$ cm^{-3}; T_i, n_i min 0.1 times max.   Poloidally constant on separatrix.
- $\Phi = 0$; Lorentz collisions
- For Tempest: resolution npol*nrad*nE*nμ = 50*40*40*50
- Caveats:
  - Different versions of Lorentz collisions:
    - Tempest run is with Lorentz with constant n and T (= values at inner bounary).
    - XGC run is with Lorentz with local (and periodically updated) n and T.
  - Different boundary conditions, and this should matter!
    - Tempest: specify f_{in} on boundary
    - XGC: continued collisionless orbits on boundary
  - VERY preliminary. 1st run-of-kind for TEMPEST.

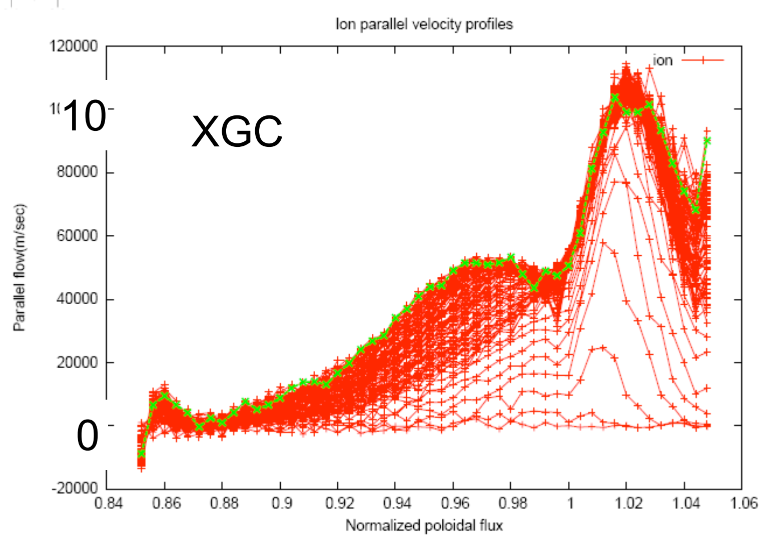
TEMPEST-XGC Divertor comparison: results similar to expected degree

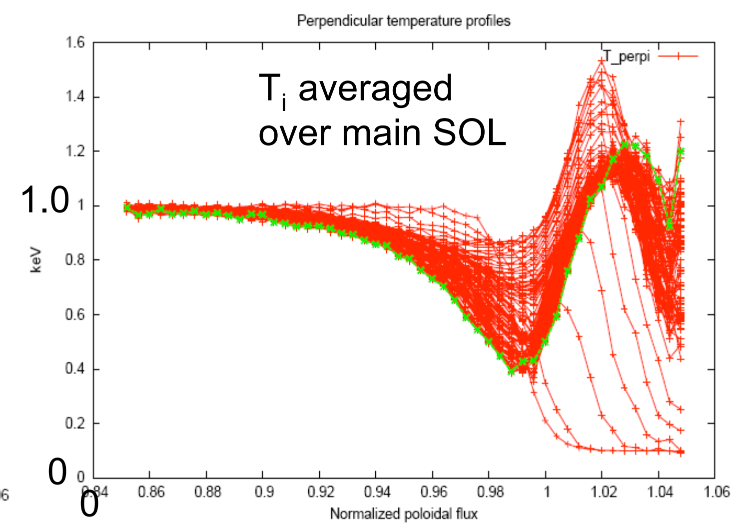
Edge Simulation Laboratory



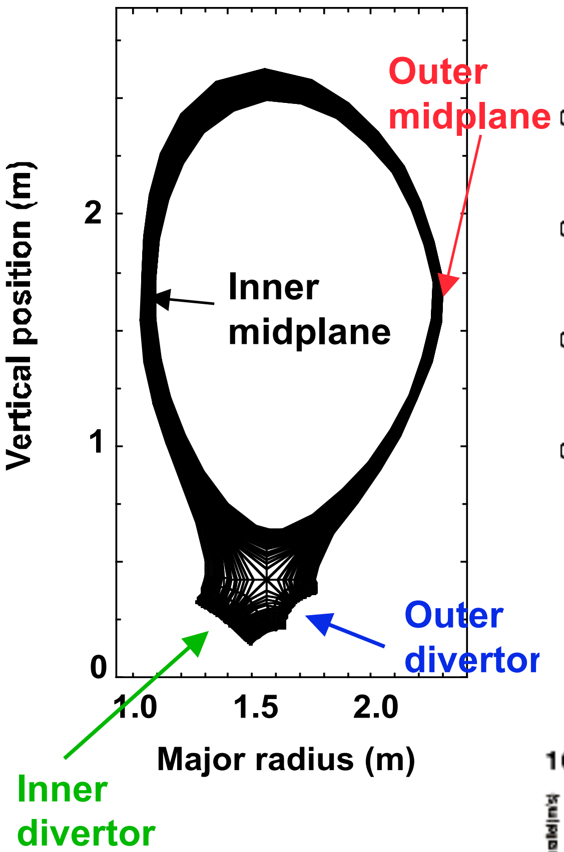


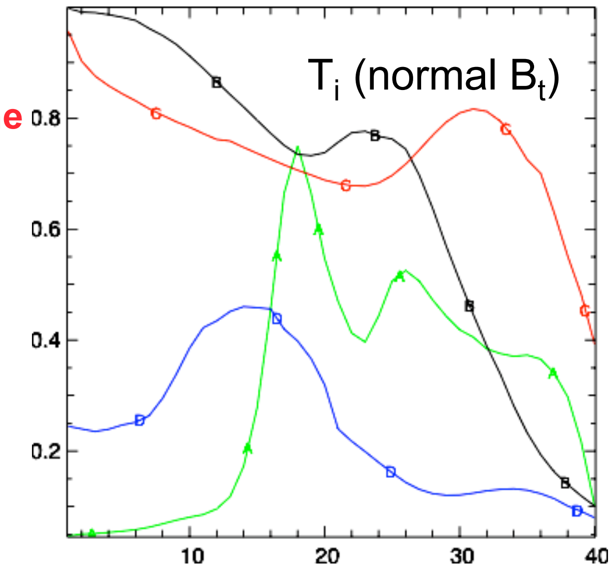


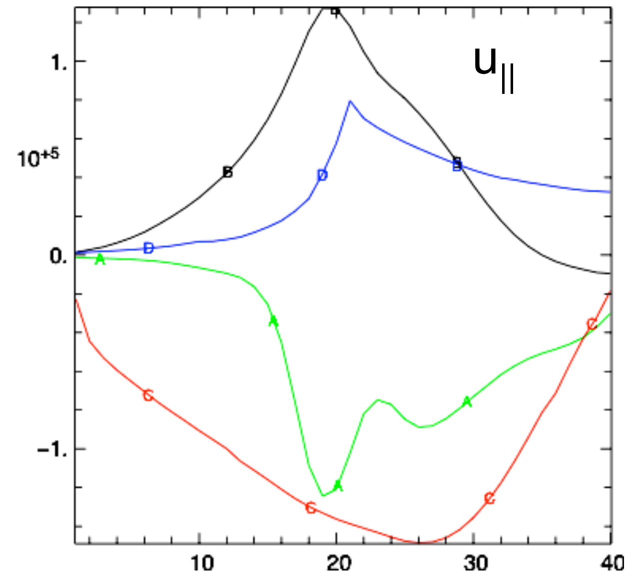


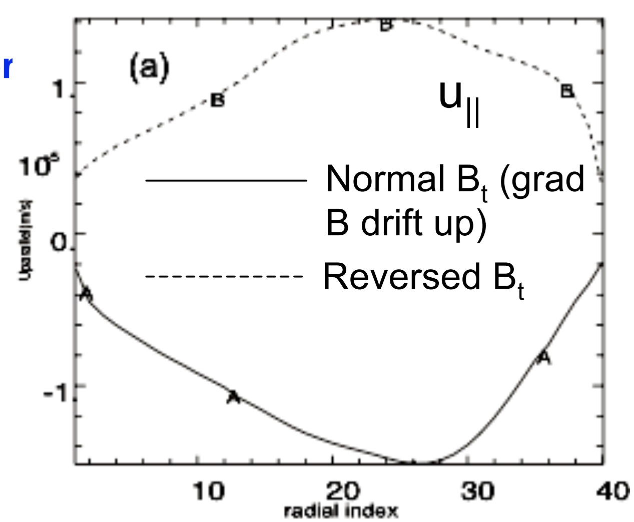


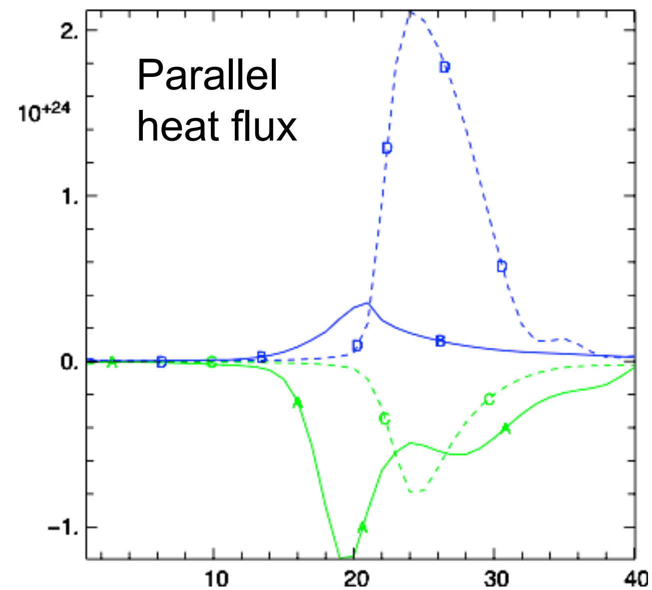
Tempest divertor neoclassical test shows reasonable poloidal dependence and intuitive asymmetries







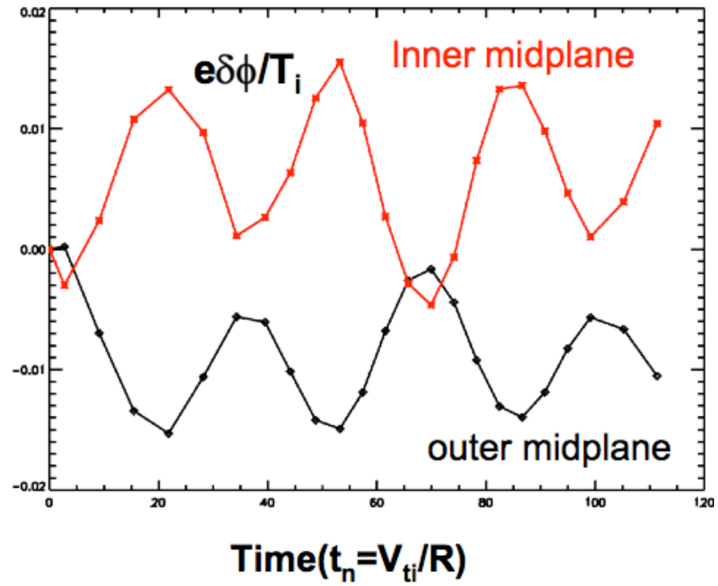




Down (up) grad B drift loads inner (outer) divertor, consistent with direction of bananas

TEMPEST IS MOVING INTO 5D SIMULATION

- In addition to toroidal advection test described earlier, preliminary low-resolution studies have been done of
  - Stable drift wave
  - Ion-temperature gradient instability



$$\omega^{sim}/\omega_{*n} \sim 1.11$$

OUTLINE

- The challenge of the edge for kinetic simulation
- Remarks on formalism
- The major approaches: PIC and continuum
- Survey of 2D+ kinetic edge simulation efforts
- Summary of recent results from ESL codes (TEMPEST, EGK)
- Conclusions

Conclusions

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- Kinetic simulation is needed for quantitative edge prediction
- Gyrokinetics is applicable but traditional formulations require extension; appropriate theory developed but must be simplified for computational tractability
- Two major approaches, PIC and continuum, each with certain advantages and disadvantages
- At least six efforts worldwide in 2D or 3D (spatial) simulation
  - complementary approaches
  - interesting progress
- Edge Simulation Laboratory (ESL) codes (Tempest, EGK) producing interesting 4D physics (neoclassical, GAMs) and first steps to 5D; also providing valuable lessons for a new ESL code now beginning
- Look forward to exciting progress between now and PET-12.